5-2019

Linear Sediment Control Best Management Practice Assessment across Three Distinct Eco-Regions of South Carolina

Daniel Dixon
Clemson University, dgdixon@g.clemson.edu

LINEAR SEDIMENT CONTROL BEST MANAGEMENT PRACTICE ASSESSMENT
ACROSS THREE DISTINCT ECO-REGIONS
OF SOUTH CAROLINA

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Plant and Environmental Sciences

---

by
Daniel G. Dixon
May 2019

Accepted by:
Dr. Charles V. Privette, III, Committee Chair
Dr. Calvin B. Sawyer
J. P. Johns

ABSTRACT

Erosion and sediment loss vary widely across distinct ecoregions. Regulations on construction runoff require improved sediment and erosion control practices to decrease total suspended solids (TSS) and turbidity. This study measures the efficiency of three different best management practices (BMPs) with and without the application of polyacrylamide (PAM) in three distinct regions of South Carolina. Sediment tubes, rock ditch checks (RDC), and rock ditch checks with washed stone (RDC-WS) were evaluated to determine the effects of adding PAM. These BMPs were placed within constructed channels on active highway construction projects. Half-inch rain events or greater that produced runoff were analyzed to determine the removal efficiency of these BMPs on turbidity and TSS. Analyses were conducted to not only determine the effects of PAM, but also each BMP. Results from this study demonstrate that treating construction runoff with combinations of BMPs and PAM reduces sediment discharge from active linear construction sites.

Based on collected data, it was observed that both RDC and RDC-WS with a PAM treatment were most effective in reducing turbidity with an average turbidity decrease of 58-63%. Wattles with a PAM treatment reduced turbidity values on average by 36%. Without PAM, a small increase in turbidity by an average of 5% occurred for RDC-WS while RDCs showed a 57% increase. These increases are partly believed to be caused by resuspension of sediment in the channel. Wattles without PAM decreased turbidity by an average of 26%. It was also observed that RDCs, RDC-WS, and wattle

structures with PAM decreased mean TSS values. Based on this research and site observations, proper maintenance and regular inspections must be a priority to reduce turbidity and TSS. Infrequent or improper BMP maintenance can result in higher TSS and lower trapping efficiencies.

ACKNOWLEDGMENTS

I would like to thank my advisors, Dr. Charles Privette and Dr. Calvin Sawyer for the opportunity and funding to stay in Clemson these past two years and earn this degree. They have given me sound advice on everything from hobbies to careers, and for that I am truly thankful. Additionally, Dr. Privette, as well as my committee members, Dr. Calvin Sawyer and J. P. Johns, provided their time, experience and guidance to help me complete this project. I would also like to thank Dr. Privette and Dr. Sawyer for introducing me to the need for progressive and evolving stormwater management as well as the assortment of interesting projects outside of my thesis work that I have been exposed to during my time working with them. J. P. Johns provided his time and experience in the professional field to ensure streamlined research. Dr. Patrick Gerard was of great assistance with his knowledge of applied statistics and inspiring patience in showing me the wide array of statistical analysis options available.

I would next like to thank SCDOT for their funding and support of this research. Ray Vaughn was essential in his role of providing us with research sites and connecting us with helpful contractors. Clara Farley and Russ Touchberry with Infrastructure Consulting Engineering, who supplied a coastal research site on such short notice. Dan David who served as a mentor upon my start and has provided constant guidance on navigating the rigors of graduate school. Jacob Burkey with Woolpert who provided guidance on project installation. Jeremy Pike who has been tremendously generous with his knowledge and expertise.

Finally, I would like to recognize individuals who were a part this project through actions made before my time. Kaolin Operations Manager in Langley, SC with Imerys North America Ceramics, donated 3 tons of Paragon® (trade name for Kaolinite). Applied Polymer Systems, Inc. provided several large quantities of their 700 Series Silt Stop Polyacrylamide Erosion Control Powder® for our research purposes.

TABLE OF CONTENTS

Table of Contents (Continued)

Page

LIST OF TABLES

LIST OF FIGURES

List of Figures (Continued)

Figure | Page

CHAPTER ONE
INTRODUCTION

Active construction projects are subject to dramatically increased levels of erosion due to the lack of vegetative ground cover and heavy traffic through the site. Rates of erosion are typically 1000-2000 times the levels of erosion generated in forested lands and 10-20 times that of agricultural lands (EPA, 2005). The costs associated with accelerated rates of erosion are not solely monetary; rapid erosion also negatively impacts biological and aesthetical properties of a region. However, it is estimated that accelerated erosion can directly cost up to two billion dollars annually through damage to water storage, treatment and conveyance systems, and the necessity to dredge waterways to ensure accessibility (Clark 1985, Pimental et al. 1995, Borelli et al. 2017).

When rain falls on bare soil, particles are detached and transported by runoff. Sand particles (diameter between 2 mm and 0.05 mm) settle out in a matter of seconds or minutes, but small colloid particles such as clay (dia. < 0.0002 mm) can stay in suspension for hundreds of days under natural conditions (McLaughlin and McCaleb, 2014). Larger particles are easily removed by conventional sediment control practices, while small particles are very difficult to remove. These small suspended particles cause runoff to have high turbidity. Turbidity is a visual measurement and directly measures light scattered by suspended particles in a water sample, measured in Nephelometric Turbidity Units (NTUs). Turbidity is an indirect measurement of suspended matter in a water sample. High turbidity caused by suspended sediment is disruptive to natural systems and can be harmful to organisms (EPA, 2012). To remove sediment and reduce turbidity, it is advantageous to use flocculation.

Flocculation is the adherence of soil particles together to where they are then heavy enough to settle out of the water column. Polyacrylamide (PAM) in the anionic form is the preferred flocculant material for environmental applications due to its low aquatic toxicity. Past research which has shown it can be very effective at turbidity reductions (Sojka et al., 2007).

Traditional sediment control best management practices (BMPs) are designed to remove total suspended solids but are ineffective at reducing turbidity caused by fine suspended particles (Bhardwaj and McLaughlin, 2008, Berry, 2012). Therefore, it is necessary to investigate how PAM can be used with sediment control BMPs in order to reduce turbidity of stormwater runoff. PAM can be applied to BMPs through active or passive systems. Active systems require energy inputs to add PAM to turbid runoff. Passive systems cause runoff to mix with PAM as it flows across and through sediment control practices, without an additional energy source. One passive method is the spreading of dry granular PAM on sediment control structures. Research has shown significant turbidity reductions from such an approach, in both controlled and construction site settings (Berry, 2012, McLaughlin et al., 2009).

Studies with PAM have shown that PAM was significantly more effective at TSS and turbidity reduction during initial storm events than in subsequent events when no re-application is present (Soupir et al., 2004; McLaughlin and Brown, 2006; Babcock and McLaughlin, 2013). Rabiou (2005) explored this phenomenon by keeping the overall application rate constant and comparing it to a “split” application where half the dose was applied initially, and the second half applied halfway through the simulated storm event. The result was a more effective reduction in soil detachment and loss for the split application. This suggests a potential benefit to re-application when PAM is used as an erosion prevention measure.

In 2009, the Environmental Protection Agency established a numerical effluent limitation of turbidity exiting active construction sites. The disturbance of 20 acres or more was subject to effluent values under 280 NTUs (EPA 2009). However, this ruling was stayed in 2015. Turbidity effluent limits are expected to be revisited in the future, as such, there is a need for a better understanding of turbidity treatment options.

The majority of research with PAM has been done in controlled field-testing environments at universities and research experiment stations. This is desirable because it enables many factors to be controlled which are otherwise unpredictable. However, it is also necessary to explore how PAM can be integrated into construction site sediment control BMPs under actual site and storm conditions. This has been done to some extent, but not in the state of South Carolina. The main objectives of this research project are as follows:

1. Compare the effectiveness of sediment tubes, rock ditch checks (RDC), and rock ditch checks with washed stone (RDC-WS) on reducing turbidity and TSS.
2. Investigate PAM’s ability to reduce turbidity of stormwater runoff on active construction sites.
3. Investigate the effect of regional differences on treating turbidity and TSS.

CHAPTER TWO
LITERATURE REVIEW

Erosion

Erosion is the gradual weathering of the Earth's surface by means of detachment, transport, and deposition of sediment. Natural erosion is driven by wind, water, ice and other natural agents. It is then transported and deposited by means of sedimentation. Erosion is significantly accelerated by human and animal activities. Soil texture, structure, and percentage of organic matter affect a soils erodibility (EPA, 1990). One of the leading anthropogenic causes of accelerated erosion is construction. Construction projects disturb and remove vegetative cover. Vegetation naturally slows the velocity of runoff and helps maintain the soils infiltration capacity. Erosion rates from construction sites typically are 10 to 20 times greater than agricultural lands and 1,000 to 2,000 times greater than those of forested lands (EPA, 2005). Soil erosion removes more than 90 percent of sediment by weight in urbanizing areas where most construction activities occur (Canning, 1988).

High erosion rates from construction sites have many negative impacts on neighboring waterbodies that can affect commercial fisheries, conveyance facilities, and water storage. The cost of sediment related damages from accelerated erosion is estimated to be between $3.0 billion to $3.5 billion, with only about $1.0 billion to $1.2 billion coming from cropland erosion. This estimate does not include biological or aesthetic damages (Clark, 1985).

Sedimentation

When soil is eroded, it is called sedimentation or sediment transport. The detached soil is then relocated by wind or water produced by storms. When the water velocity slows, the sediment is deposited. The soil transferred is often deposited where it is unusable and can lead to reduced water quality and weakens the integrity of dams and reservoirs.

Turbidity

Turbidity is the measurement of reflected and scattered light that results from striking soil particles in a fluid sample. Turbidity is a relatively easy characteristic to measure and estimate sediment loads from construction sites if reliable relationships between turbidity and total suspended solids (TSS) are established (Perkins et al. 2017). Turbidity is most often measured in Nephelometric Turbidity Units (NTUs), originally used by Nephelometers, or nephelometric turbidimeters. This technique uses a turbidity probe that includes a light beam and light detector. The light beam sends light into a sample where it is scattered by suspended solids in the sample. Some of the scattered light then strikes the photodiode detector which converts the amount of light it detects into a numeric value. The more particles that are detected, the higher the NTU value.

Higher turbidity increases water temperatures because suspended soil particles absorb more heat. This, in turn, reduces the concentration of dissolved oxygen (DO). Additionally, higher turbidity also reduces the amount of light penetrating the water, which reduces photosynthesis and the production of DO. As the particles settle, they can cover the stream bottom. This problem is especially prevalent in slower waters, smothering fish eggs and benthic macro invertebrates (EPA, 2012). Suspended clay and silt sized particles are also known to adsorb biological and chemical contaminants (LaGrega et al. 2001). These smaller soil particles are more likely to stay suspended in the water column due to their lighter densities and have the ability to travel great distances, transporting pollutants with them. Suspended materials have a number of adverse effects on the biotic community. Biological contaminants including *Fecal Coliform* specifically *Escherichia coli,* can attach to soil particles, that jeopardizes recreational and drinking water.

The potential of a numeric limitation on stormwater runoff by regulation and an increased interest in preserving waters of the United States, has generated an elevated interest in research related to turbidity reduction. It is important to remember that turbidity is not a measure of the quantity of suspended solids in a sample, but instead, an aggregate measure of the combined scattering effect of the water sample's suspended particles on an incident light source.

Total Suspended Solids

Construction runoff often carries solid materials, including organic and inorganic, that are suspended in the water column. These materials are referred to as Total Suspended Solids (TSS). These would include soil particles, plankton and industrial wastes. High concentrations of suspended solids can lower water quality by absorbing light. Waters then become warmer and lessen the ability of the water to hold oxygen necessary for aquatic life. Because aquatic plants also receive less light, photosynthesis decreases, and less oxygen is produced. The combination of warmer water, less light and less oxygen makes it impossible for some forms of life to exist. Suspended solids affect life in other ways. They can clog fish gills, reduce growth rates, decrease resistance to disease, and prevent egg and larval development. Particles that settle out can smother fish eggs and those of aquatic insects, as well as suffocate newly-hatched larvae. The material that settles also fills the spaces between rocks and makes these microhabitats unsuitable for various aquatic insects (NDDOH, 2016).

Turbidity Meters Units

Table 2.1: Instrument specific turbidity units established by USGS and ASTM (USGS, 2004).

Reporting units corresponding to different turbidity instrument designs [nm, nanometers; °, degree]		
	Light Wavelength	
Detector geometry	**White or broad band** (with a peak spectral output of 400-680 nm)	**Monochrome** (spectral output typically near infrared, 780-900 nm)
Single Illumination Beam Light Source		
At 90° to incident beam	Nephelometric Turbidity Unit (NTU)[a]	Formazin Nephelometric Unit (FNU)[b]
At 90° and other angles. An instrument algorithm uses a combination of detector readings, which may differ for values of varying magnitude.	Nephelometric Turbidity Ratio Unit (NTRU)	Formazin Nephelometric Ratio Unit (FNRU)
At 30°± 15° to incident beam (backscatter)	Backscatter Unit (BU)	Formazin Backscatter Unit (FBU)
At 180° to incident beam (attenuation)	Attenuation Unit (AU)	Formazin Attenuation Unit (FAU)
Multiple Illumination Beam Light Source		
At 90° and possibly other angles to each beam. An instrument algorithm uses a combination of detector readings, which can differ for values of varying magnitude.	Nephelometric Turbidity Multibeam Unit (NTMU)	Formazin Nephelometric Multibeam Unit (FNMU)

[a] Use of NTU: limited to instruments that comply with EPA Method 180.1 (U.S. Environmental Protection Agency, 1993).

[b] Use of FNU: pertains to instruments that comply with ISO 7027, the European drinking-water protocol (International Organization for Standardization, 1999), which includes many of the submersible turbidimeters that are in common use in the USGS for onsite measurements.

Flocculation and Flocculants

Small particles such as colloids (diameter < 0.0001 mm) can take months to settle out of the water column, which make them significant contributors to turbidity. One way to address the impacts of turbidity is the use of flocculants such as Polyacrylamide (PAM). PAM is a broad class of synthetic organic polymers formed by polymerization of acrylamide, with the net charge (anionic, neutral, or cationic), charge density (hydrolysis percentage), and molecular weight depending on the synthesis method (Seybold, 1994). Flocculation is the process of these small particles adhering together and building up into larger "floc" particles which settle much faster. Colloids typically have a negative surface charge. Therefore, chemicals which introduce positive charges into the system are necessary for coagulation and flocculation (Auckland Regional Council, 2004). It may seem counterintuitive that negatively charged polymers such as PAM are successful at flocculating negatively charged particles. This process is able to occur due to cation bridging with positively charged ions that are common in aquatic systems, typically Ca^{2+} (Sojka et al., 2007).

PAM can be applied in liquid or granular forms, in what is known as active and passive applications, respectively. Active dosing involves the use of regular labor to introduce the flocculant, usually involving pumping a liquid form of PAM into the flow of a sediment control system. In general, active dosing produces very reliable turbidity reductions. The costs associated with setup and maintenance limit its widespread use for construction site runoff. Passive dosing requires no external energy and involves the introduction of flocculant by placing solid or powder form into the stormwater flow, thereby "passively" dissolving it into the water. Passive application generally takes place on stormwater (BMPs) such as rock-check dams and sediment tubes (Kang et al. 2014).

Polyacrylamide Background

Polyacrylamide (PAM) is a broad term that encompasses a range of compounds varying in polymer chain length, shape, and number. Linear chain polymers are typically water soluble while cross linking chains are usually not. In addition to low aquatic toxicity, it has also been found that the presence of anionic PAM does not reduce microbial metabolic potential of soil or affect bacterial structural diversity, richness, or evenness (Entry, et al. 2013). Some common uses of anionic PAM include drinking water treatment, drilling mud, sewage sludge dewatering, paper manufacturing, clarification of juices and drinking water, thickening of animal feed, and coating of paper used in food packaging (Sojka et al., 2007). Water quality practices involving the use of PAM such as erosion prevention and sediment control is of particular interest in order to protect water bodies and meet current and potential future environmental regulations. PAM was first used during World War II to prevent erosion during construction of roadways, bridges, and runways (Wilson & Crisp 1975) however these preliminary uses included high application rates that weren't cost effective.

Recently, water soluble anionic PAM was identified as a highly effective tool for reducing erosion in agricultural settings especially with furrow irrigation. This was done by applying PAM product as a known concentrated liquid of 1-10 PPM or using the "patch method" in PAM's granular form. This is done by spreading 15-30 grams of PAM in the first "upstream" meter of a furrow, a sticky "patch" forms that dissolves the PAM into the irrigation water as it passes over. The soil's surface structure is stabilized and vastly reduces erosion. Under research conditions this method was shown to reduce erosion up to 94% (Lentz et al. 2002)

Erosion Prevention BMPs and Polyacrylamide

The end goal of erosion prevention should be to establish ground vegetation to naturally keep soil in place, as such applying seed coverage is an essential Best Management Practice (BMP). A wide array of techniques and products exist to keep soil in place before the seed establishes and some actively encourage establishment of vegetation (SCDOT, 2017).

Erosion control blankets (ECBs) are one of the primary means of protecting soil integrity. They come in large rolls that can be spread over disturbed areas. ECBs are typically made of straw, excelsior (aspen fibers), or coir (coconut husk fibers). ECBs not only retain soil structure; they also hold seeds in place for vegetation establishment. They are typically installed in areas of low flow and milder slopes. For steeper slopes and higher velocity areas, turf reinforcement mats (TRMs) are used. These are typically made of plastic meshes and can be varied in density depending on the need.

Sediment Control BMPs and Polyacrylamide

While it is impossible to stop all erosion from occurring during land disturbing activities, it is critical to stop the erosion and subsequent sedimentation from occurring through sediment control BMPs. Examples of BMPs used for sediment control include linear ditch checks and ponding structures. Ditch checks consist of a variety of materials dependent on the velocity of water moving through the channel. For faster moving water, rock ditch checks are necessary while in many water conveyance channels of lower flow, straw and other fibrous materials are used in tubular shapes wrapped in netting called sediment tubes or wattles. The sediment tubes are advantageous in that they are easier to install and typically cost less. They also can be used on tight linear roadway projects where space is limited (McLaughlin et al., 2009).

Once water moves through the channel, it is typically deposited into a sediment basin or retention pond. The excavated basin is used to contain runoff and allow for enough time so that the sediment will settle out of the water column. In the state of South Carolina, sediment basins are required and designed to trap at least 80% of sediment that enters the basin (SCDHEC, 2005).

Regardless of the BMP used, turbidity is not shown to be significantly reduced by BMPs alone. However, research has shown that TSS values can be reduced by employing stormwater BMPs in conjunction with PAM (Bhardwaj and McLaughlin, 2008; Berry, 2012). There are three typical forms of PAM used: granular, liquid, and solid blocks.

Current Specifications for Polyacrylamide

States vary on their specifications of PAM as well as their instructed uses. Some states only recommend using PAM as an erosion control agent while North Carolina and Alabama recommend using PAM as only a sedimentation control as there is research that PAM is much more effective this way (ALDOT 2012; NCDOT 2013). Florida and other states however use PAM for both erosion prevention and sediment control (FDOT 2013). More examples of how states have chosen to describe the use of PAM for sediment control can be found at the resources in Table 2.2

Table 2.2: Erosion and sediment control manuals which describe the use of PAM.

State	Link to Resource
North Carolina	http://portal.ncdenr.org/web/lr/publications
Alabama	http://www.dot.state.al.us/conweb/doc/Specifications/2012_GASP.pdf
Florida	http://www.dot.state.fl.us/rddesign/Hydraulics/files/Erosion-Sediment-
Tennessee	http://tnepsc.org/TDEC_EandS_Handbook_2012_Edition4/TDEC%20EandS%20Handbook%20 4th%20Edition.pdf
Georgia	http://www.gaepd.org/Documents/esc_manual.html
Pennsylvania	http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-87860/363-2134-
South Dakota	http://sddot.com/resources/manuals/E&SControlSW.pdf
Washington	http://www.wsdot.wa.gov/publications/manuals/fulltext/M41-10/SS2014.pdf

North Carolina has specific BMP details which include PAM, for example "Wattle with PAM" and "Temporary Rock Silt Check Type A with Excelsior Matting and PAM." North Carolina specifies 4 ounces of PAM be applied to each BMP at installation and then reapplied after every rain event of 0.5 inches or greater (NCDOT, 2008).

CHAPTER THREE

LINEAR SEDIMENT CONTROL BEST MANAGEMENT PRACTICE ASSESSMENT ON TURBIDITYACROSS THREE DISTINCT ECO-REGIONS OF SOUTH CAROLINA

Abstract

This study measures the efficiency of three different best management practices (BMPs) with and without the application of polyacrylamide (PAM) in three distinct regions of South Carolina. Sediment tubes, rock ditch checks (RDC), and rock ditch checks with washed stone (RDC-WS) were evaluated to determine the effects of adding PAM. These BMPs were placed within constructed channels on active highway construction projects. Half-inch rain events or greater that produced runoff were analyzed to determine the removal efficiency of these BMPs on turbidity and TSS. Analyses were conducted to not only determine the effects of PAM, but also each BMP. Results from this study demonstrate that treating construction runoff with combinations of BMPs and PAM reduces sediment discharge from active linear construction sites.

Based on collected data, it was observed that both RDC and RDC-WS with a PAM treatment were most effective in reducing turbidity with an average turbidity decrease of 58-63%. Wattles with a PAM treatment reduced turbidity values on average by 36%. Without PAM, a small increase in turbidity by an average of 5% occurred for RDC-WS while RDCs showed a 57% increase. These increases are thought to be partially caused by resuspension of sediment in the channel. Wattles without PAM decreased turbidity by an average of 26%. Across the state, if no PAM was applied,

higher turbidity was often observed in conjunction with all BMPs. Across all storm events the mean turbidity without PAM was 211 NTUs while with PAM the mean turbidity was 151 NTUs.

Introduction

Active construction projects are subject to dramatically increased levels of erosion due to the lack of vegetative ground cover and heavy traffic through the site. Rates of erosion are typically 1000-2000 times the levels of erosion generated in forested lands and 10-20 times that of agricultural lands (EPA, 2005). The costs associated with accelerated rates of erosion are not solely monetary; rapid erosion also negatively impacts biological and aesthetical properties of a region. However, it is estimated that accelerated erosion can directly cost up to two billion dollars annually through damage to water storage, treatment and conveyance systems, and the necessity to dredge waterways to ensure accessibility (Clark 1985, Pimental et al. 1995, Borelli et al. 2017).

When rain falls on bare soil, particles are detached and transported by runoff. Sand particles (diameter between 2 mm and 0.05 mm) settle out in a matter of seconds or minutes, but small colloid particles such as clay (dia. < 0.0002 mm) can stay in suspension for hundreds of days under natural conditions (McLaughlin and McCaleb, 2014). Larger particles are easily removed by conventional sediment control practices, while small particles are very difficult to remove. These small suspended particles cause runoff to have high turbidity.

Turbidity is a visual measurement and directly measures light scattered by suspended particles in a water sample, measured in Nephelometric Turbidity Units

(NTUs). Turbidity is an indirect measurement of suspended matter in a water sample. High turbidity caused by suspended sediment is disruptive to natural systems and can be harmful to organisms (EPA, 2012). To remove sediment and reduce turbidity, it is advantageous to use flocculation.

Flocculation is the adherence of soil particles together to where they are then heavy enough to settle out of the water column. Polyacrylamide (PAM) in the anionic form is the preferred flocculant material for environmental applications due to its low aquatic toxicity. Past research which has shown it can be very effective at turbidity reductions (Sojka et al., 2007).

The SCDOT design criteria for stormwater runoff that drains to a single outfall (drainage area for the specific single outlet at the location of exit at the SCDOT project property or rights-of way boundary) from land disturbing activities which disturb ten (10) acres or more, is to meet a TSS removal efficiency of 80%. While these BMPs are effective in removing TSS, they are often ineffective at reducing turbidity caused by fine suspended particles (Bhardwaj and McLaughlin, 2008, Berry, 2012).

Therefore, it is necessary to investigate how PAM can be used with sediment control BMPs in order to reduce turbidity of stormwater runoff. PAM can be applied to BMPs through active or passive systems. Active systems require energy inputs to add PAM to turbid runoff. Passive systems cause runoff to mix with PAM as it flows across and through sediment control practices, without an additional energy source. One passive method is the spreading of dry granular PAM on sediment control structures. Research has shown significant turbidity reductions from such an approach, in both controlled and construction site settings (Berry, 2012, McLaughlin et al., 2009).

Studies on erosion prevention with PAM have shown that PAM was significantly more effective at turbidity reduction during initial storm events than in subsequent events when no re-application is present (Soupir et al., 2004; McLaughlin and Brown, 2006; Babcock and McLaughlin, 2013). Rabiou (2005) explored this phenomenon by keeping the overall application rate constant and comparing it to a “split” application where half the dose was applied initially, and the second half applied halfway through the simulated storm event. The result was a more effective reduction in soil detachment and loss for the split application. This suggests a potential benefit to re-application when PAM is used as an erosion prevention measure.

The majority of research with PAM has been done in controlled field-testing environments at universities and research experiment stations. This is desirable because it enables many factors to be controlled which are otherwise unpredictable. However, it is also necessary to explore how PAM can be integrated into construction site sediment control BMPs under actual site and storm conditions. This has been done to some extent, but not in the state of South Carolina. The objectives for this research are as follows:

1. Evaluate the effect of different BMPs on turbidity.
2. Evaluate the effect of BMPs with granular PAM on turbidity.
3. Evaluate regional effects on turbidity reductions and BMPs.

Procedures

Experimental Sites

In September of 2013, automated sampling instrumentation and 15.24 cm Parshall flumes were deployed in a runoff conveyance channel associated with the widening of SC Highway 9 in Boiling Springs, SC. The channel runs parallel to Holden Drive, which runs perpendicular to and down-grade from Highway 9 as shown in Figure 3.1. The channel had a slope of 5% and then flattened out at the bottom of the hill, before discharging into a sediment basin. The channel was lined with turf reinforcement matting in the center and erosion control blankets on the sides for stabilization. It received runoff that was piped from the project along Highway 9 and discharged through a 76.2 cm diameter concrete pipe at the top of the channel. The drainage area contributing runoff to the channel was 2.8 hectares, with 0.9 hectares of that being roadway. Based on the NRCS Web Soil Survey, the area of interest was 90-95% Cecil sandy loam with small areas of other Cecil series soils. The sloped portion of the channel contained four rock ditch checks made of Class A rip rap, and the flat part of the channel contained two additional rock ditch checks. Instrument stations were established at the top and bottom of the sloped section, enclosing the first four rock ditch checks as the practices to be researched. The channel is shown in Figure 3.2 from the 76.2 cm culvert.

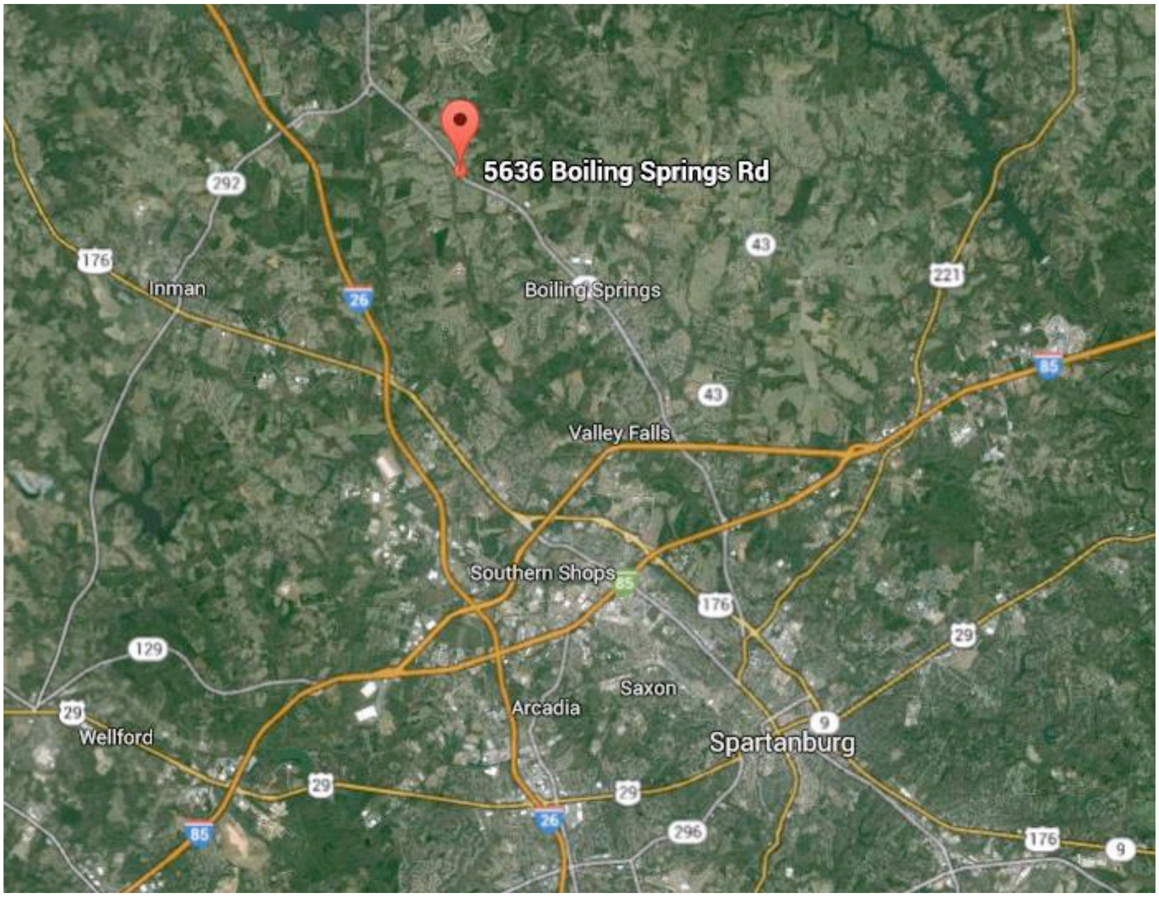


Figure 3.1: Location map showing the location of the Upstate project site.


Figure 3.2: Upstate research station showing instrumentation.

Likewise, in December 2014, automated sampling instrumentation was deployed and staked in a runoff conveyance channel associated with the widening of SC Highway 52 in Darlington, SC., the channel ran parallel to Hwy 52. The channel was soil based with sparse vegetation on the sides for stabilization, had a slope of 1%, and received direct runoff from the project along Hwy 52, and then discharged into a sediment basin. The drainage area contributing runoff to the channel was 8.33 hectares, with 0.1 hectares of that being the road. Based on the NRCS Web Soil Survey, the area of interest was 51% Foxworth sand, 25% Alpin sand, 23% Johnston sandy loam, and a small area of Autryville sand. Instrumentation was installed at the top of channel and bottom of the channel enclosing three ditch checks made of either coiler waddles or Class A rip rap faced with washed stone.

Figure 3.3: Location map showing the location of the Mid-State research site.

Figure 3.4: Mid-State research channel showing instrumentation.

Finally, automatic sampling equipment and 15.24 cm Parshall flumes were installed in the coastal plains of South Carolina. The first linear conveyance channel monitored was off SC Highway 41 in Charleston, SC adjacent to a bridge replacement over the Wando River. This site was eventually relocated due to lack of flow and progression of the construction. However, data was collected for two adequately sized storms in this channel. The site consisted of three wattles in a low sloped channel typical of the region. The predominant soil types were a sand and silt mix. The second site used was in Summerville SC, off exit ramp 197 on Interstate 26 east bound and had a slope of 0.05%. Flumes were placed to enclose four BMP structures. Three BMP types were monitored, these were sediment tubes, rock check dams with class A riprap, and the same rock check dams with size 57 stone on the face. NRCS Web Soil Survey indicated that the roughly 0.81-hectare drainage was 100% Pantego Sandy Loam.

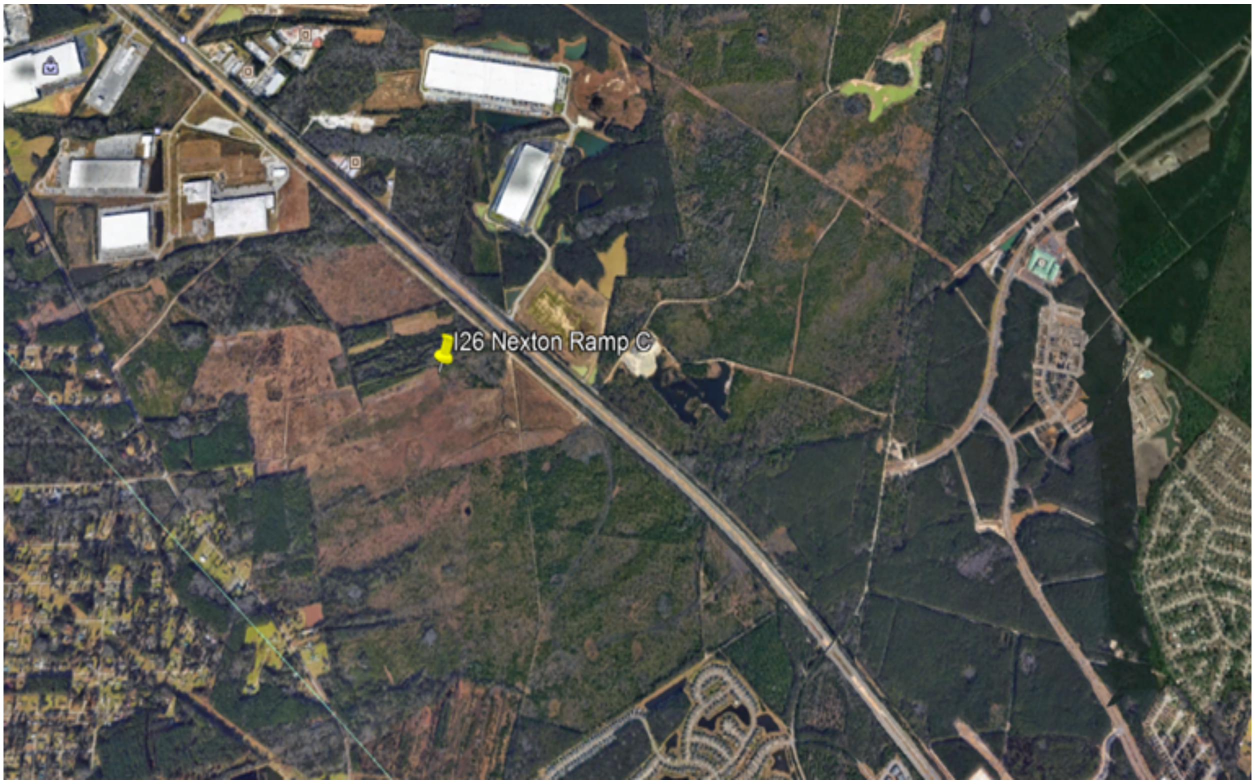


Figure 3.5: Location map showing the location of the Coastal research site.

The Coastal and Upstate monitoring sites consisted of a 15.24 cm Parshall flume with a Campbell Scientific CS451 pressure transducer to measure flow depth. From this depth, the flow rate through the flume was calculated using the following equation (Teledyne ISCO, 2011).

1. $Q = 2.06 \times H^{1.58}$

Where

Q = Flow rate of water runoff through the flume, measured in cubic feet per second (cfs), and

H = The water level measured in the flume, measured in feet.

The flumes were installed with 45-degree plywood wing walls. Installation involved trenching into the channel to create a level place for the flume and walls, orienting them correctly, attaching the wing walls, and then backfilling with the excavated material. Also, in the flume, a Campbell OBS500 turbidity meter was installed. The mid-state monitoring site did not use a Parshall flume, top of channel data was collected from within the channel with an ISCO Teledyne AV Probe to record depth of the runoff, and a Campbell Scientific OBS 500 turbidimeter. Flow was measured using runoff depth and known dimensions of the channel, the dimensions and flow calculations for this channel can be found in Appendix D.

A Teledyne ISCO 6712 Portable Sampler was installed at each station with its sampler intake anchored to the ground immediately downstream of the flume. Instruments were wired to a Campbell CR206x data logger for logging and control purposes. These instruments were chosen so that real-time field turbidity data could be recorded, and samples could be taken for laboratory analysis.

Data and sample collection were triggered based on presence of runoff through the Parshall flumes at the upstate and coastal sites. When the pressure transducer detected 0.03 m of water, the turbidity meter started recording observations every minute, and the ISCO Sampler began a time-based sampling protocol. The code for this programming can be found in Appendix C. The trigger depth of 0.03 meters was chosen for two reasons. The first is that 0.03 meters of depth in a 15.24 cm Parshall flume is equivalent to 0.015 cm/s of flow and this is the smallest measurement in the recommended flow measurement range for the flume (Teledyne ISCO, 2011). This flow measurement is important for flow weighting calculations and general knowledge of the flow conditions in the channel. The second reason is that 0.03 meters of water is enough to expect that the ISCO intake strainer will be submerged and able to pull samples.

Figure 3.6. Coastal Research Station showing instrumentation and Parshall flume.

The ISCO sampling protocol is shown in Table 3.1 below. Samples of 750 mL were taken when the sampler was enabled and then every five minutes for the first thirty minutes of runoff. After this period, samples were taken every fifteen minutes. This protocol emphasized catching the “first flush” of sediment from a storm when turbidity is known to be high (Tempel, 2011). It also ensured sampling for the entirety of smaller storm events as well as a substantial initial portion of longer duration storm events. Even when samples were not being collected, real-time turbidity data was always collected when runoff was present in the channel.

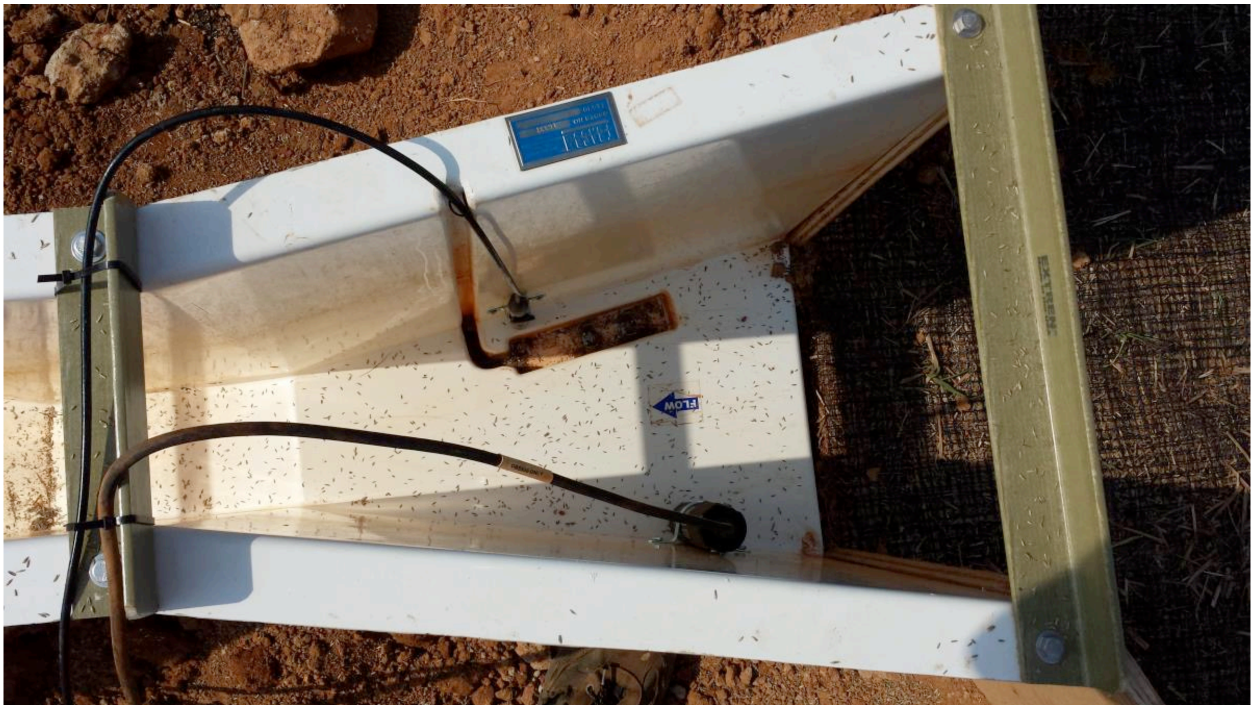


Figure 3.7: Probes mounted in the 15.24 cm Parshall flume.

Table 3.1: ISCO-Teledyne sampling schedule, activated by runoff reaching the 0.03 m. trigger point.

Bottle #	Time Since Enable [min]	Bottle #	Time Since Enable [min]
1	0	13	120
2	5	14	135
3	10	15	150
4	15	16	165
5	20	17	180
6	25	18	195
7	30	19	210
8	45	20	225
9	60	21	240
10	75	22	255
11	90	23	270
12	105	24	285

A "base station" was also established at the site to record rainfall and enable telecommunication. This consisted of a Campbell CR1000 data logger connected to a tipping bucket rain gage, a RF401 radio, and cellular modem. Programming was established such that one could communicate with the system remotely using Campbell Loggernet software. Rainfall data was available by connecting to the CR1000 data logger. Flow rate and turbidity data was available by communicating through the base station to the instrument stations using radio telemetry. Figure 3.8 shows the instrument station at the bottom of the channel which included the base station (white box and large antenna) and rain gauge.

Figure 3.8: Image of a “base station” installed at the Upstate location, equipped with a rain gauge and cellular modem.

Background data was collected for runoff events on BMPs with no PAM treatment, followed by a period of PAM application and reapplication to evaluate turbidity reduction using PAM. Each PAM application involved the sprinkling of 100 grams of granular APS #705, #710, #712 PAM for the upstate site, coastal region, and mid-state respectively.

The specific PAM product used for each site was based on jar test results. A 200 mL volume of deionized water was placed in a container with 5 mg of dried soil collected from the research sites. The jar was inverted repeatedly until a homogenous mixture was seen. Baseline turbidity analysis measurements were recorded, the turbidity analysis is described in the next section. Afterwards, a 0.05 mL dissolved PAM product was injected into the jar and turbidity readings were noted, this process was repeated several times to determine the best application rate of PAM and which PAM product was most efficient in reducing turbidity. The most effective granular PAM for the region was applied upon the top and upstream face of the BMP structures, such that runoff was likely to make contact. During this study, PAM was reapplied after periods of rain which caused runoff events. This was compared to the specification to reapply after every 1.27 cm rain event which is used in North Carolina NCDOT (NCDOT, 2013). Observations made support it being an effective rule for reapplying PAM.

During periods of PAM treatment, PAM was reapplied as soon as possible after rain events which caused runoff and triggered the ISCO samplers. In addition to the reapplication of PAM, regular maintenance involved collecting sample bottles from the ISCO samplers and making sure all instruments were in working order. This included removal of sediment deposits and debris and rinsing of probes. Rinsing of the tip of the pressure transducer and lenses of the OBS500 after storm events was effective at preventing inaccurate "false zero" readings due to sediment accumulation.

Lab Analysis

A Hach 2100AN Laboratory Turbidimeter was used to measure turbidity of all samples following Standard Method 2130 B (APHA, 2005). The Hach has a range up to 10,000 NTUs with the following accuracy specifications (Hach, 2012).

±2% of reading plus 0.01 NTU from 0-1000 NTU

±5% of reading from 1000 NTU to 4,000 NTU

±10% of reading from 4,000 NTU to 10,000 NTU

Each sample was agitated by inverting and shaking the sample bottle for 5 seconds or until sediment was evenly suspended, displaying a homogenous solution. A 20mm aliquot was pulled from the sample bottle using a pipette, one sample was collected for each bottle. The sample was then transferred into a Hach turbidimeter vial. The vial was wiped clean, carefully inverted 10 times, and placed into the turbidimeter. The Hach turbidimeter measures turbidity by sending light through the vial and measuring reflectance back in NTUs. After turbidity analysis, samples were analyzed for TSS using Standard Method 2540 B (APHA, 2005).

Particle Size Analysis

For each region in this study a particle size analysis was conducted. Soil samples were collected from the research sites, multiple samples per site were analyzed from upstream and in channel locations. The analysis consisted of weighing 10g of 2mm or less sized soil, drying them in an oven over night at 104° Celsius and placing them in a nest of sieves that has a top to bottom size order from 2, 1, 0.5, 0.25, 0.125, 0.063 mm and a catch pan at the base. The sieves were then shaken using a motorized sieve shaker for 3 minutes. The weight of each sieve was recorded along with the sieve plus sample weight. Empty the contents of each sieve into a 1L graduated cylinder. The sieves are then placed in order over a funnel draining to the 1L graduated cylinder. Using deionized water, the sieves and catch pan were rinsed to wash the remaining sediment into the graduated cylinder, continue to rinse until the graduated cylinder is filled to 1L. The cylinders contents are then agitated using a magnet and magnetic plate. Using a 25mL pipette, samples were extracted at different time intervals as seen in Table 3.2 based on an initial sample temperature taken in degrees Celsius. The samples are extracted at 150mm from the top of the graduated cylinder for the first 4 steps and then raised to 100mm and 50mm respectively for the remaining two sample intervals. The collected samples are deposited into beakers that are then dried over night at 104° Celsius and weighed once pulled from the oven and placed in a desiccator for 30 minutes.

Table 3.2: Table of timed intervals for extracting samples for particle size analysis, based on particle size and water temperature in degrees Celsius.

Particle Size (cm)	**Time to Fall 150 mm @21**	**Time to Fall 150 mm @22**	**Time to Fall 150 mm @23**	**Time to Fall 150 mm @24**	**Time to Fall 150 mm @25**	**Time to Fall 150 mm @26**	**Time to Fall 150 mm @27**	**Time to Fall 150 mm @28**	**Time to Fall 150 mm @29**	**Time to Fall 150 mm @30**
0.0063	0.00.41	0.00.40	0.00.39	0.00.38	0.00.38	0.00.37	0.00.36	0.00.35	0.00.34	0.00.34
0.0031	0.02.50	0.02.46	0.02.42	0.02.39	0.02.35	0.02.32	0.02.28	0.02.25	0.02.22	0.02.19
0.0016	0.10.39	0.10.24	0.10.10	0.09.56	0.09.42	0.09.29	0.09.17	0.09.05	0.08.54	0.08.43
0.0008	0.42.37	0.41.37	0.40.39	0.39.45	0.38.50	0.37.58	0.37.08	0.36.21	0.35.34	0.34.50
	Time to Fall 100 mm @21	**Time to Fall 100 mm @22**	**Time to Fall 100 mm @23**	**Time to Fall 100 mm @24**	**Time to Fall 100 mm @25**	**Time to Fall 100 mm @26**	**Time to Fall 100 mm @27**	**Time to Fall 100 mm @28**	**Time to Fall 100 mm @29**	**Time to Fall 100 mm @30**
0.0004		1.53.38	1.50.58	1.48.25	1.45.59	1.43.33	1.41.14	1.39.02	1.36.56	1.34.51
	Time to Fall 50 mm @21	**Time to Fall 50 mm @22**	**Time to Fall 50 mm @23**	**Time to Fall 50 mm @24**	**Time to Fall 50 mm @25**	**Time to Fall 50 mm @26**	**Time to Fall 50 mm @27**	**Time to Fall 50 mm @28**	**Time to Fall 50 mm @29**	**Time to Fall 50 mm @30**
0.0002		3.47.16	3.41.56	3.36.50	3.31.58	3.27.06	3.22.28	3.18.03	3.13.53	3.05.46

Statistical Analysis

Due to the relatively small runoff sample size collected during storm events, a combination of descriptive statistics and statistical graphics were utilized to describe apparent trends in the relationship between turbidity parameters, flow characteristics, BMPs, and PAM. The collected lab data did not have a normal distribution; therefore, the Wilcoxon rank sum test was used to compare the samples. The Wilcoxon rank sum test (also called the Mann-Whitney U test, the Mann-Whitney-Wilcoxon (MWW), or the Wilcoxon-Mann-Whitney test) is a nonparametric test of the null hypothesis. Unlike the t-test it does not require the assumption of normal distributions, it is nearly as efficient as the t-test on normal distributions. Analysis of variance (ANOVA) was also tested to determine if there were significant statistical differences between BMPs.

Samples were time weighted based on the sampling increment shown in Table 3.1 and averaged over the total storm period.

Results and Discussion

Appendix A contains the data sets that are relevant to this study. To evaluate data, criteria for a "storm event" had to be established. It was difficult to create one clear rule to satisfy all storm events so professional judgment was used in order to establish storm events that most accurately portrayed the relationship of turbidity observations to storm and flow characteristics. This involved the consideration of two factors, the period of rainfall and the period of runoff in the channel.

The first criterion for a storm event was simply the period of time that it rained, inclusive of all readings shown by the rain gage in proximity to the bulk of the rain. This satisfied many events. It did not sufficiently define events which were long in duration with periods of variable intensity. In this case, consideration was given to the period during which runoff occurred. In instances where it rained constantly but with variable intensity for one or more days, distinctly separate runoff events sometimes occurred. When this was the case, the rain contributing to these separate runoff events were considered separate storm events. A final criterion which applied to all storm events was that they must generate 0.03 meters of runoff in the Parhsall flumes in order to trigger data collection. Any rain event which did not generate at least 0.1 feet of runoff was not considered significant for this study.

Samples were collected from both top of channel and bottom of channel stations. The weighted mean turbidity values were established for both top of channel (inflow) and bottom of channel (outflow). The determined means and corresponding percent changes were compared by location in channel, BMP, presence of PAM application, and by region. Peak values, the average of the highest and lowest 5% of turbidity determined from the samples, was examined to evaluate the difference in numerical peaks in Table 3.5. This is important if a numeric effluent limit is established. The Wilcoxon rank sum test and ANOVA were run on these samples to determine statistical significance. Table 3.3 demonstrates a summary of analysis observations. RDC without PAM was the only BMP at the upstate site to not show a statistically significant difference, the ANOVA analysis of JMP suggests that there was no significant difference between inflow and outflow turbidity values, indicating the RDC did nothing to reduce turbidity (p value = 0.8198). Figure 3.10 shows graphical representations of the analysis of variance and standard deviations between the treatment data sets.

Turbidity During Storm Events — Statistical Analysis Summary

Treatment	Time Weighted NTU AVG	Time Weighted NTU AVG	NTU
	IN	OUT	Diff
C-RDC	39.83	42.88833333	-8%
C-RDC	118.8245614	421.1666667	-254%
US-RCD	1640.066667	183.02	89%
US-RCD	1034.783333	2608.82	-152%
US-RCD	1209.55	742.3095238	39%
			-57%
C-RDC	116.59	44.43833333	62%
C-RDC	317.522807	153.1315789	52%
US-RDC	390.547619	89.67	77%
			64%
MID-RDC-WS	3796.15	5126.416667	-35%
MID-RDC-WS	3309.42	7545.95	-128%
MID-RDC-WS	2018.574074	1418.9	30%
US-RDC-WS	1367.190476	866.3333333	37%
US-RDC-WS	2608.82	1189.904762	54%
C-RDC-WS	161.1833333	148.9166667	8%
C-RDC-WS	299.38	317.24	-6%
			-6%
MID-RDC-WS			
MID-RDC-WS	2420.2		
US-RCD-WS	1165.190476	784.7952381	33%
C-RDC-WS	1198.55	188.0166667	84%
			58%
C-SEDTUBES	3533.93	3458.083333	2%
C-SEDTUBES	3272.983333	1663.416667	49%

Treatment	Time Weighted NTU AVG	Time Weighted NTU AVG	NTU
MID-W			
			26%
C-SEDTUBES	1070.066667	528.32	51%
C-SEDTUBES	306.0649123	177.8216667	42%
MID W	1999.6	1367.19	32%
MID W	8073.754386	6341.183333	21%
			36%

Averages without PAM	Averages with PAM

Table 3.3: Table of laboratory analysis observations; turbidity reductions.

One parameter that stands out with respect to both BMP effectiveness and PAM application is regions. For BMPs installed in the midlands, it was noticed that elevated turbidities on inflow existed as compared to the two other regions. Observations of this site showed much higher sediment loads and depositions within the channels whereby sands comprised much of the transported sediment. At times, this sediment yield resembled a bed load transport that is often times found in natural sand bed channels. Extensive internal erosion and scour was occurring within the channel bottoms and side walls. As a point of interest with respect to the midlands site, while with no PAM an increase in turbidity was observed reflecting the internal erosion that occurred, when PAM was applied, even under these conditions, turbidity was reduced.

Table 3.4: Summary of parameters for lab sample dataset — ANOVA, and non-parametric statistical tests of the null-hypothesis (Ho = No difference between TOC and BOC, p value (Pr > F) > .05 then reject Ho and accept Ha).

TURBIDITY				
Identifier	**Statistical Test**	**p value**	**Statistical Test**	**Pr > F**
Upstate RDC	WILCOXAN	0.0094	Anova	0.0461
Upstate RDC	WILCOXAN	0.0001	Anova	0.0001
Upstate RDC-WS	WILCOXAN	0.005	Anova	0.001
Upstate RDC-WS	WILCOXAN	0.0001	Anova	0.0003
Midstate W	WILCOXAN	0.0042	Anova	0.0077
Midstate W	WILCOXAN	0.1692	Anova	0.1827
Midstate RDC - WS	WILCOXAN	0.0125	Anova	0.002
Midstate RDC - WS	WILCOXAN	0.0005	Anova	0.0009
Coastal W	WILCOXAN	0.0006	Anova	0.0007
Coastal W	WILCOXAN	0.0003	Anova	0.002
Coastal RDC-WS	WILCOXAN	0.328	Anova	0.3259
Coastal RDC-WS	WILCOXAN	0.3589	Anova	0.0006
Coastal RDC	WILCOXAN	0.0001	Anova	0.0001
Coastal RDC	WILCOXAN	0.0008	Anova	0.0002

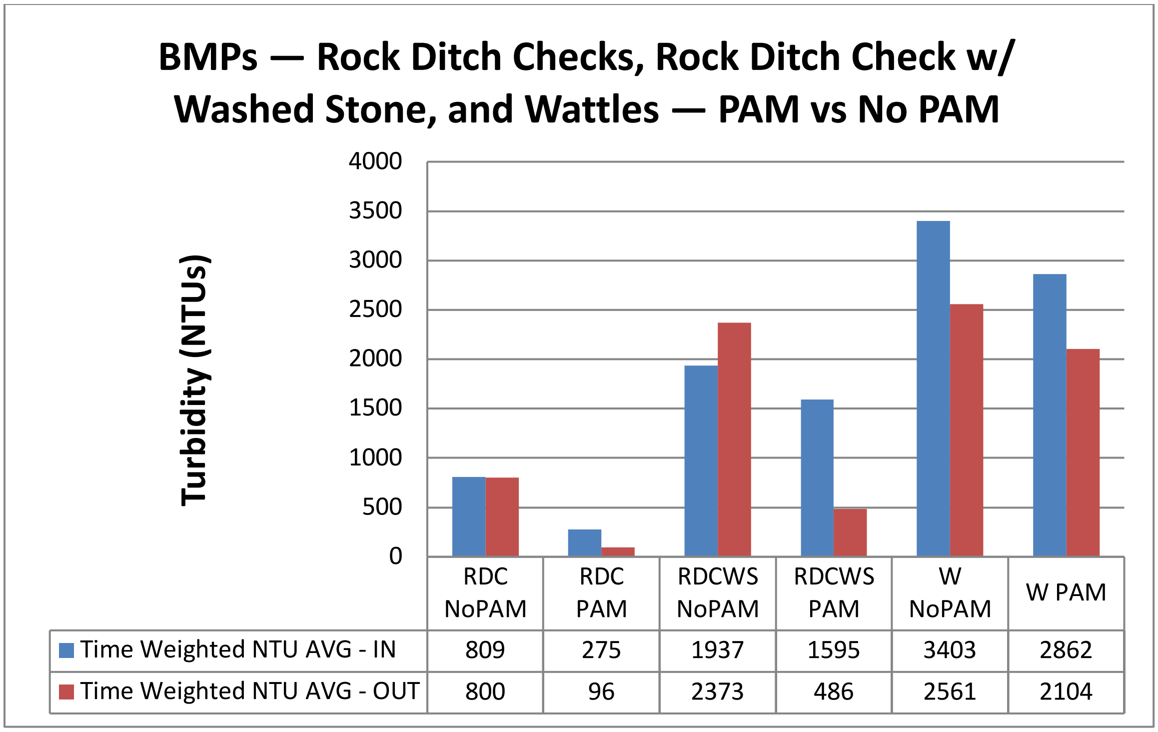


Figure 3.9: Summary showing lab analysis of percentage change of turbidity values, total mean (NTU).

Turbidity values without a PAM application often showed a percentage increase after passing through the channel. This could be due to maintenance of BMPs as shown in Appendix D. Mean percentage changes illustrate that PAM was effective in treating turbidity, however, peak turbidity values either decreased or were minimal in their increase as shown in Table 3.9. The Wilcoxon and ANOVA analysis of JMP shows that there was a significant difference between all inflow and outflow turbidity values, as shown in Table 3.6., Treatments of BMPs or BMPs plus PAM affected outflow turbidity (p value < 05). Figures 3.12 and 3.13 show graphical representations of the analysis of variance and standard deviations between the two data sets. The predominant sand soil type indicates re-suspension of soil particles is doubtful. Particle size analysis indicated soils for the research sites are as follows. The upstate soil was comprised of 39.9% sand, 18.1% silt, and 42% clay. Soils in the mid-state project were comprised of 91.25% sand, 3.00% silt, and 5.75% clay. Particle size analysis indicated soils in the coastal area were comprised of 78% sand, 19% silt, and 3% clay.

Table 3.5: Summary of lab data set turbidity parameters for all BMPs with and without a PAM application within 7 days prior to a storm event.

NTU		
	PAM	
	N	**Y**
BMP TYPE	Mean	Mean
RDC	804.5817	197.0754
RDC-WS	2155.313	840.0747
W	2974.224	2478.099

In order to show the effect of PAM treatment on turbidity, Table 3.6 and Figure 3.10 were created. These show percent turbidity reductions plotted against storm size and assigned symbols based on the location where the qualified storm occurred. All BMPs used at their respective locations were included in Figure 3.10 in order to increase sample size and attempt to evaluate whether PAM treatment made an impact on turbidity reduction. Percent reduction and total rainfall were determined to be the most descriptive datasets. Percent reduction was chosen because it standardized the data and kept the x-axis within the same order of magnitude. Total rainfall was chosen because the number of runoff events omitted information about rain that occurred but did not cause substantial runoff. Table 3.6 displays the overall effectiveness of PAM throughout the state on all

BMPs sampled, mean percent change between inflow and outflow is the parameter being measured. Figure 3.11 is the graphical representation of this analysis.

Table 3.6: Summary parameters of presence of PAM comparison

PAM (Y/N)	Number	MEAN PERCENT CHANGE	Std Error	Lower 95%	Upper 95%
N	616	–14.45	25062.3	19109	23075
Y	498	53.94	14515.0	12107	16923

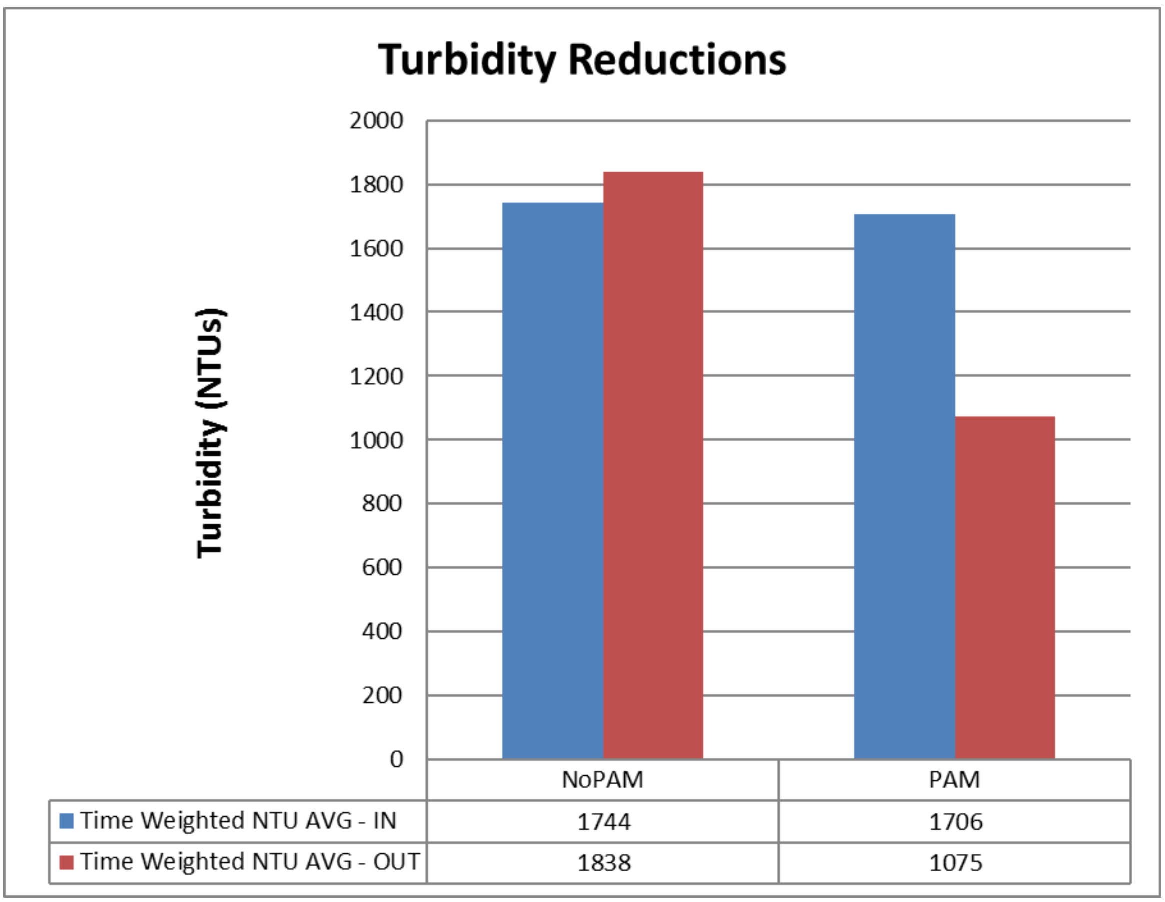


Figure 3.10: Graph of mean turbidity percent changes with and without the use of PAM.

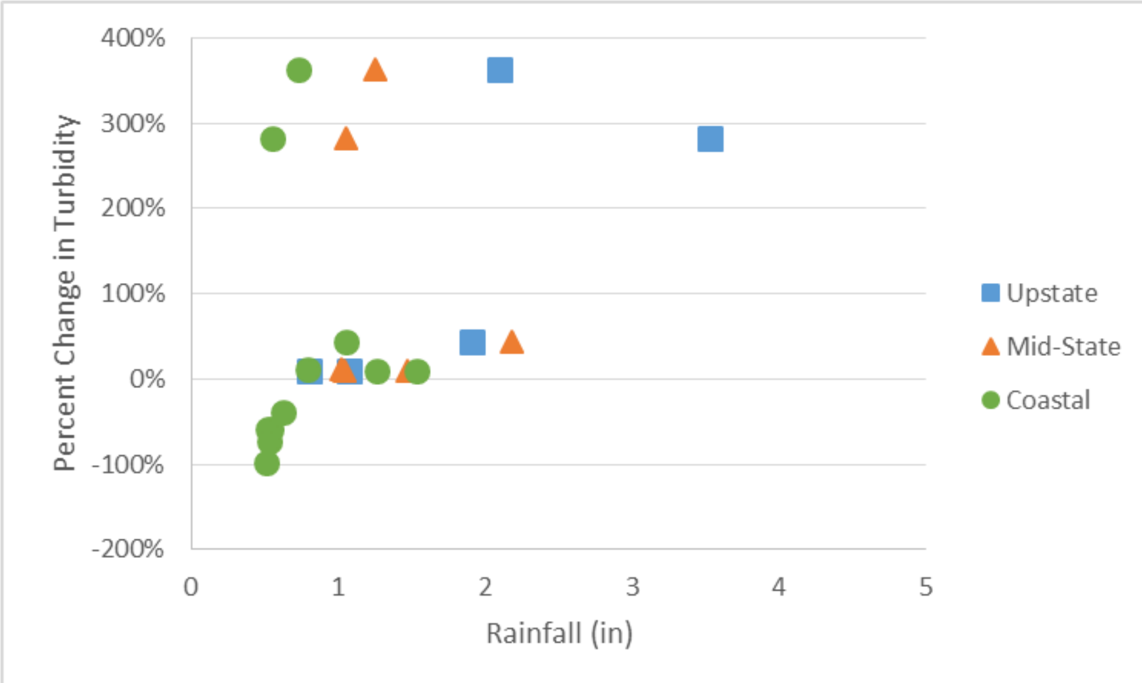


Figure 3.11: Percent turbidity reduction plotted with storm size and rainfall.

Conclusions

This analysis evaluated the impact on turbidity of sediment tubes, rock ditch checks (RDCs) and rock ditch checks with washed #57 stone on the upstream face (RDC-WS) both with and without PAM at three active roadway construction sites in the upstate, mid-state, and coastal regions of South Carolina.

Based on this research, the use of PAM on linear construction sites can reduce turbidity. PAM with either wattles, RDC, or RDC-WS consistently showed turbidity reductions. The predominately sandy soil at the mid-state research site made it less likely for re-suspension of deposited sediment to occur as was seen in the upstate and coastal data.

Applying PAM to the BMPs before a storm event decreased turbidity on average by 54%. Without the use of PAM, turbidity was increased on average by 14% for all BMPs used in this study. However, the extent of both percentage reduction and numeric reduction varied quite a bit based on storm and runoff flow characteristics. Therefore, if it is ever necessary or desired to meet a specific numeric limit, granular PAM applied to wattles, RDC, or RDC-WS may or may not be adequate to meet such a limit. Downstream sediment traps or ponds could potentially help achieve this goal by giving the runoff additional settling time after PAM is introduced. The observations made during periods of PAM application in this study generally support the benefit of treating BMPs prior to any notable storm event.

CHAPTER FOUR
ASSESSING LINEAR SEDIMENT CONTROL BEST MANAGEMENT PRACTICES ON TOTAL SUSPENDED SOLIDS ACROSS THREE DISTINCT ECO-REGIONS OF SOUTH CAROLINA

Abstract

This study measures the efficiency of three different best management practices (BMPs) with and without the application of polyacrylamide (PAM) in three distinct regions of South Carolina. Sediment tubes, rock ditch checks (RDC), and rock ditch checks with washed stone (RDC-WS) were evaluated to determine the effects of adding PAM. These BMPs were placed within constructed channels on active highway construction projects. Half-inch rain events or greater that produced runoff were analyzed to determine the removal efficiency of these BMPs on TSS. Analyses were conducted to not only determine the effects of PAM, but also each BMP. Results from this study demonstrate that treating construction runoff with combinations of BMPs and PAM reduces sediment discharge from active linear construction sites.

Based on collected data, it was observed that both RDC and RDC-WS with a PAM treatment were most effective in reducing TSS with an average TSS decrease of 46-49%. Wattles with a PAM treatment reduced TSS values on average by 31%. Without PAM, a small decrease in TSS by an average of 2% occurred for RDC-WS while RDCs showed a 76% increase. These increases are thought to be partially caused by resuspension of sediment in the channel. Wattles without PAM decreased TSS by an average of 7%. Across the state, if no PAM was applied, higher TSS was often observed

in conjunction with all BMPs. Across all storm events the mean TSS without PAM was 1797 mg/L while with PAM the mean TSS was 818 mg/L.When PAM was used in conjunction with the BMPs, TSS decreased for RDC, RDC-WS, and wattles respectively.

Introduction

Active construction projects are subject to dramatically increased levels of erosion due to the lack of vegetative ground cover and heavy traffic through the site. Rates of erosion are typically 1000-2000 times the levels of erosion generated in forested lands and 10-20 times that of agricultural lands (EPA, 2005). The costs associated with accelerated rates of erosion are not solely monetary; rapid erosion also negatively impacts biological and aesthetical properties of a region. However, it is estimated that accelerated erosion can directly cost up to two billion dollars annually through damage to water storage, treatment and conveyance systems, and the necessity to dredge waterways to ensure accessibility (Clark 1985, Pimental et al. 1995, Borelli et al. 2017).

When rain falls on bare soil, particles are detached and transported by runoff. Sand particles (diameter between 1 mm and 0.1 mm) settle out in a matter of seconds or minutes, but small colloid particles such as clay (dia. < 0.0001 mm) can stay in suspension for hundreds of days under natural conditions (McLaughlin and McCaleb, 2014). This means that larger particles are easily removed by conventional sediment control practices, and small particles are very difficult to remove. TSS is a physical measurement using a collected runoff sample and weighing the sample pre and post dehydrating. Water evaporates and leaves the weight of the solids remaining. These could include soil particles, plankton and industrial wastes. Much of the controversy with TSS regulations is based on design versus actual standards of sediment control structures. Theoretically, sediment control structures are designed to trap a certain percentage of suspended sediment. However trapping efficiency is difficult to and costly to measure, thus federal, state, and local entities lack the resources to adequately ensure proper functioning of all sediment control structures. In addition, TSS analysis requires lab work and cannot be easily or quickly determined in the field, which creates difficulties in detecting discharge permit violations. The SCDOT design criteria for stormwater runoff that drains to a single outfall (drainage area for the specific single outlet at the location of exit at the SCDOT project property or rights-of way boundary) from land disturbing activities which disturb ten (10) acres or more, is to meet a TSS removal efficiency of 80%. Therefore, it is desirable and necessary to research how TSS can be reduced with individual sediment control BMPs across varying regions with distinct soil types.

The majority of research with TSS has been done in controlled field-testing environments at universities and research experiment stations. This is desirable because it enables many factors to be controlled which are otherwise unpredictable. However, it is also necessary to explore how TSS can be adequately controlled from usage of construction site sediment control BMPs under actual site and storm conditions. This has been done to some extent, but not in the state of South Carolina. This study evaluates the efficiency of three different (BMPs) in treating TSS. TSS was examined with and without the application of polyacrylamide (PAM) passively applied at a rate of 100 grams per BMP in channel.

This research was conducted on linear construction projects across three regions of South Carolina. Instruments were deployed at the top and bottom of runoff conveyance channels to measure the change to TSS as runoff traveled through a series of stormwater Best Management Practices (BMPs). The objectives were as follows:

1. Evaluate the effect of different BMPs on TSS.
2. Evaluate the effect of different BMPs with granular PAM on turbidity
3. Evaluate the effect of BMPs applied in distinct regions of South Carolina on TSS.
4. Examine the relationship between TSS and turbidity.

Procedures

In September of 2013, automated sampling instrumentation and 6-inch Parshall flumes were deployed in a runoff conveyance channel associated with the widening of SC Highway 9 in Boiling Springs, SC. The channel ran parallel to Holden Drive, which runs perpendicular to and down-grade from Highway 9 as shown in Figure 4.1 below. The channel had a slope of 5% and then flattened out at the bottom of the hill, before discharging into a sediment basin. The channel was lined with turf reinforcement matting in the center and erosion control blankets on the sides for stabilization. It received runoff that was piped from the project along Highway 9 and discharged through a 76.2 cm diameter concrete pipe at the top of the channel. The drainage area contributing runoff to the channel was 2.8 hectares, with 0.9 hectares of that being roadway. Based on the NRCS Web Soil Survey, the area of interest was 90-95% Cecil sandy loam with small areas of other Cecil series soils. The sloped portion of the channel contained four rock ditch checks made of Class A rip rap, and the flat part of the channel contained two additional rock ditch checks. Instrument stations were established at the top and bottom of the sloped section, enclosing the first four rock ditch checks as the practices to be researched. The channel is shown in Figure 4.2 from the 76.2 cm culvert.

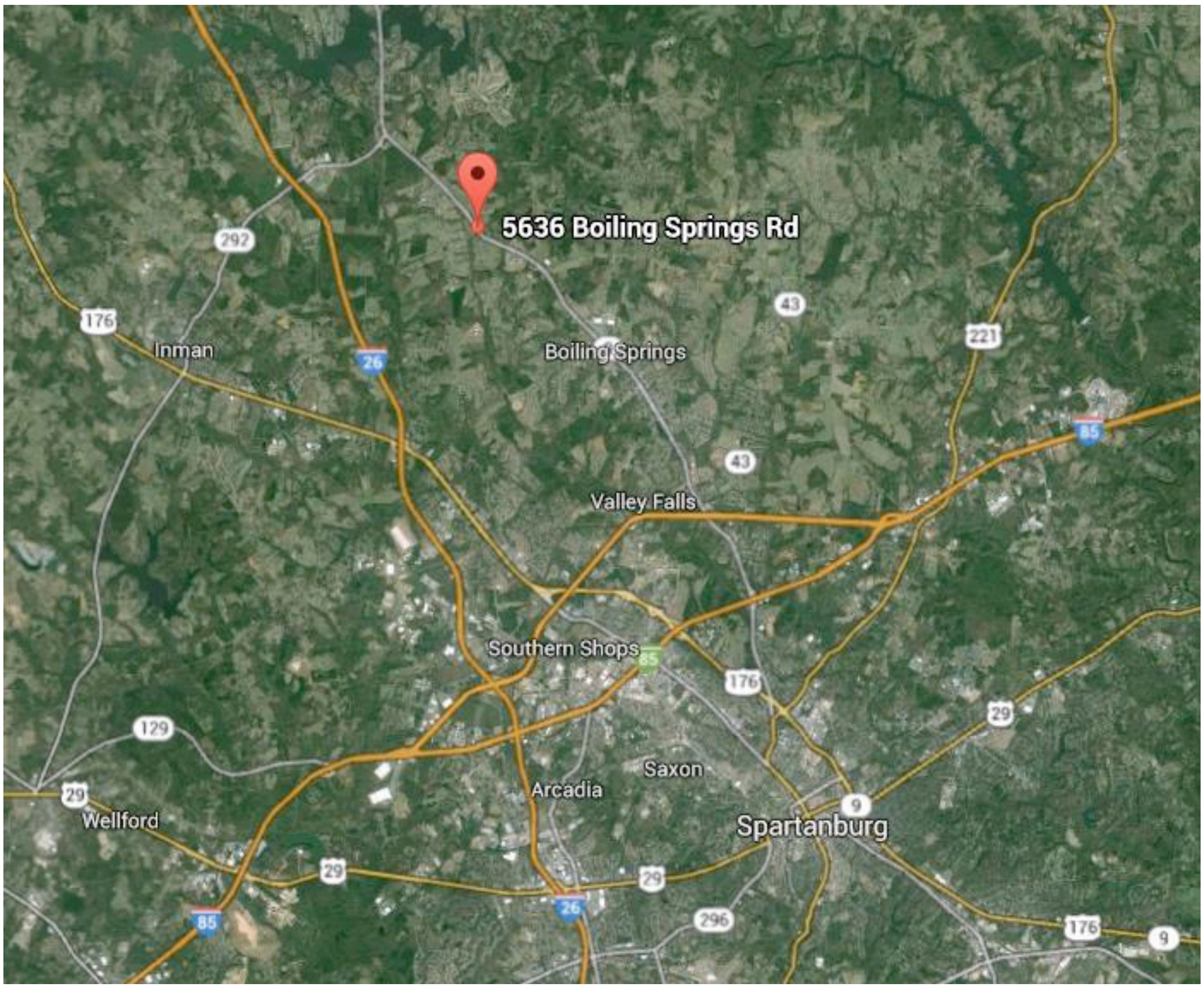


Figure 4.1: Location map showing the location of the Upstate project site.

Figure 4.2: Upstate research station showing instrumentation.

Likewise, in December 2014, automated sampling instrumentation was deployed and staked in a runoff conveyance channel associated with the widening of SC Highway 52 in Darlington, SC., the channel ran parallel to Hwy 52. The channel was soil based with sparse vegetation on the sides for stabilization, had a slope of 1%, and received direct runoff from the project along Hwy 52, and then discharged into a sediment basin. The drainage area contributing runoff to the channel was 8.33 hectares, with 0.1 hectares of that being the road. Based on the NRCS Web Soil Survey, the area of interest was 51% Foxworth sand, 25% Alpin sand, 23% Johnston sandy loam, and a small area of Autryville sand. Instrumentation was installed at the top of channel and bottom of the channel to enclosing three ditch checks made of either coiler waddles or Class A rip rap faced with washed stone.

Figure 4.3: Location map showing the location of the Mid-State research site.


Figure 4.4: Mid-State research channel showing instrumentation.

Finally, automatic sampling equipment and 15.24 cm Parshall flumes were established in the coastal plains of South Carolina. The first linear conveyance channel monitored was off SC Highway 41 in Charleston, SC adjacent to a bridge replacement over the Wando River. This site was eventually relocated due to lack of flow and progression of the construction. However, data was collected for two adequately sized storms in this channel. The site consisted of three sediment tubes in a low sloped channel typical of the region. The predominant soil types were a sand and silt mix. The second site used was in Summerville SC, off exit ramp 197 on Interstate 26 east bound and had a slope of 0.05%. Flumes were placed to enclose four BMP structures. Three BMP types were monitored, sediment tubes, rock check dams with class A riprap, and the same rock check dams with size 57 stone on the face. NRCS Web Soil Survey indicated that the roughly 0.81-hectare drainage was 100% Pantego Sandy Loam.

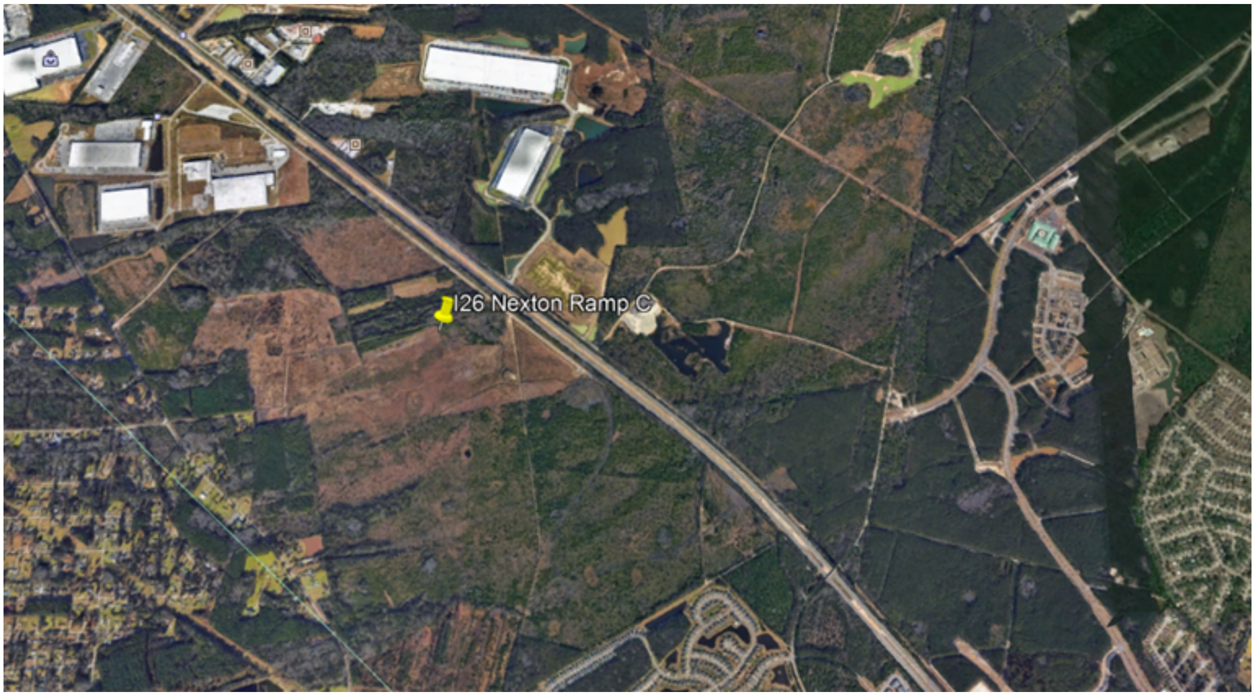


Figure 4.5: Location map showing the location of the Coastal research site.

Instrument stations were established at the start of each conveyance channel before the first BMP and after the last BMP to establish “Before and After” TSS readings to evaluate the efficiency of the BMPs.

The Coastal and Upstate monitoring sites consisted of a 15.24-cm Parshall flume with a Campbell Scientific CS451 pressure transducer to measure flow depth. From this depth, the flow rate through the flume was calculated using the following equation (Teledyne ISCO, 2011).

1. $Q = 2.06 \times H^{1.58}$

Where

Q = Flow rate of water runoff through the flume, measured in cubic feet per second (cfs), and

H = The water level measured in the flume, measured in feet.

The flumes were installed with 45-degree plywood wing walls. Installation involved trenching into the channel to create a level place for the flume and walls, orienting them correctly, attaching the wing walls, and then backfilling with the excavated material. Also, in the flume, a Campbell OBS500 turbidity meter was installed. The Mid-State monitoring site did not use a Parshall flume, TOC data was collected from within the channel with an ISCO Teledyne AV Probe to record depth of the runoff, and a Campbell Scientific OBS 500 turbidimeter. Flow was measured using runoff depth and known dimensions of the channel.

A Teledyne ISCO 6712 Portable Sampler was installed at each station with its sampler intake anchored to the ground immediately downstream of the flume. Instruments were wired to a Campbell CR206x data logger for logging and control purposes. These instruments were chosen so that real-time field turbidity data could be recorded, and samples could be taken for laboratory analysis.

Data and sample collection were triggered based on presence of runoff through the Parshall flume. When the pressure transducer detected 0.03 meters of water, the turbidity meter started recording observations every minute, and the ISCO Sampler began a time-based sampling protocol. The code for this programming can be found in Appendix C. The trigger depth of 0.03 meters was chosen for two reasons. The first is that 0.03 meters of depth in a 15.24 Parshall flume is equivalent to 0.015 cms of flow and this is the smallest measurement in the recommended flow measurement range for the flume (Teledyne ISCO, 2011). This flow measurement is important for flow weighting calculations and general knowledge of the flow conditions in the channel. The second reason is that 0.1 feet of water is enough to expect that the ISCO intake strainer will be submerged and able to pull samples.

Figure 4.6: Coastal Research Station showing instrumentation and Parshall flume.

The ISCO sampling protocol is shown in Table 4.1 below. Samples of 750 mL were taken when the sampler was enabled and then every five minutes for the first thirty minutes of runoff. After this period, samples were taken every fifteen minutes. This protocol emphasized catching the "first flush" of sediment from a storm when turbidity is known to be high (Tempel, 2011). It also ensured sampling for the entirety of smaller storm events as well as a substantial initial portion of longer duration storm events. Even when samples were not being collected, real-time turbidity data was always collected when runoff was present in the channel.

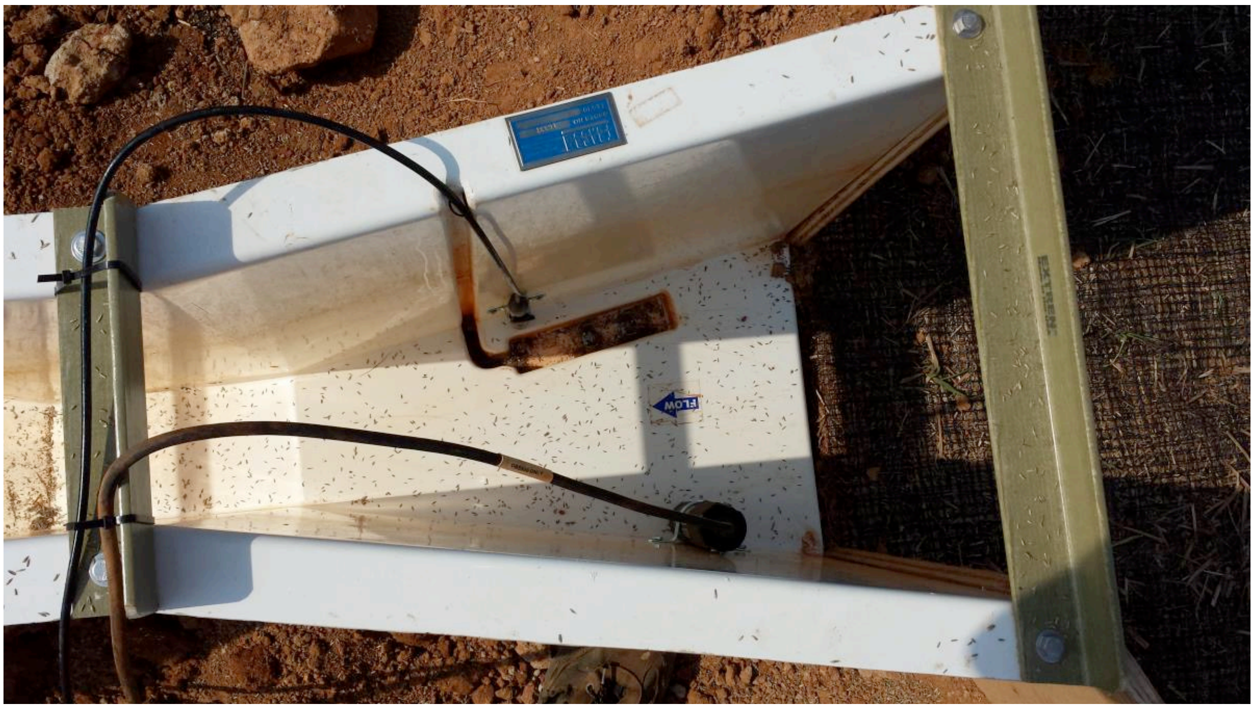


Figure 4.7: Probes mounted in the 6" Parshall flume.

Table 4.1: ISCO-Teledyne sampling schedule, activated by runoff reaching the 0.03 m. trigger point.

Bottle #	Time Since Enable [min]	Bottle #	Time Since Enable [min]
1	0	13	120
2	5	14	135
3	10	15	150
4	15	16	165
5	20	17	180
6	25	18	195
7	30	19	210
8	45	20	225
9	60	21	240
10	75	22	255
11	90	23	270
12	105	24	285

A "base station" was also established at the site to record rainfall and enable telecommunication. This consisted of a Campbell CR1000 data logger connected to a tipping bucket rain gage, a RF401 radio, and cellular modem. Programming was established such that one could communicate with the system remotely using Campbell Loggernet software. Rainfall data was available by connecting to the CR1000 data logger. Flow rate and turbidity data was available by communicating through the base station to the instrument stations using radio telemetry. Figure 8 shows the instrument station at the bottom of the channel which included the base station (white box and large antenna) and rain gage.

Figure 4.8: Image of a “base station” installed at the Upstate location, equipped with a rain gauge and cellular modem.

Sample Analysis

A Hach 2100AN Laboratory Turbidimeter was used to measure turbidity of all samples following Standard Method 2130 B (APHA, 2005). The Hach has a range up to 10,000 NTUs with the following accuracy specifications (Hach, 2012).

±2% of reading plus 0.01 NTU from 0-1000 NTU

±5% of reading from 1000 NTU to 4,000 NTU

±10% of reading from 4,000 NTU to 10,000 NTU

Each sample was agitated by inverting and shaking the sample bottle for 5 seconds or until sediment was evenly suspended. The sample was then transferred into a Hach turbidimeter vial. The vial was then wiped clean, carefully inverted 10 times, and placed into the turbidimeter. After turbidity analysis, samples were analyzed for TSS using Standard Method 2540 B (APHA, 2005).

TSS analysis was conducted by mixing the collected sample until the sediment sample appeared to be uniformly suspended. A representative sample of 40 ml was quickly withdrawn using a volumetric pipette. The alloquate was then discharged into a pre-weighed tin, transferred to the drying oven set at 104° C and allowed to set overnight. The dried samples where then cooled in a desiccator and then weighed again to obtain the TSS weights. Based upon the discharge volume, a concentration of TSS (mg/L) was obtained.

Statistical Analysis

Due to the relatively small sample size provided by storm events, a combination of descriptive statistics and statistical graphics were utilized to describe apparent trends in the relationship between turbidity parameters, flow characteristics, BMPs, and PAM. In addition, the collected data did not have a normal distribution, therefore the Wilcoxon rank sum test was used to compare the samples. The Wilcoxon rank sum test (also called the Mann-Whitney U test, the Mann-Whitney-Wilcoxon (MWW), or the Wilcoxon-Mann-Whitney test) is a nonparametric test of the null hypothesis. Unlike the t-test it does not require the assumption of normal distributions, it is nearly as efficient as the t-test on normal distributions. Analysis of variance (ANOVA) was also tested to determine if there were significant statistical differences between BMP effects.

To perform this analysis, criteria for a "storm event" had to be established. It was difficult to create one clear rule to satisfy all storm events so professional judgment was used in order to establish storm events that most accurately portrayed the relationship of turbidity observations to storm and flow characteristics. This involved the consideration of two factors, the period of rainfall and the period of runoff in the channel.

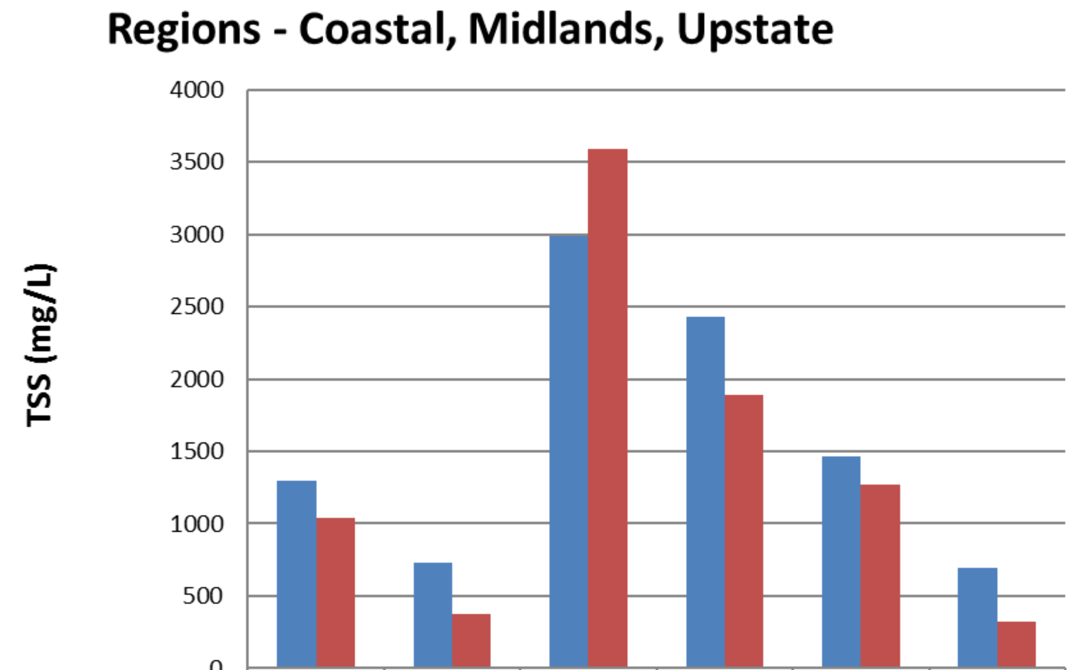
The first criterion for a storm event was simply the period of time that it rained, inclusive of all readings shown by the rain gage in proximity to the bulk of the rain. This satisfied many events. It did not sufficiently define events which were long in duration with periods of greatly variable intensity. In this case, consideration was given to the period during which runoff occurred. In instances where it rained constantly but with variable intensity for one or more days, distinctly separate runoff events sometimes occurred. When this was the case, the rain contributing to these separate runoff events were considered separate storm events. A final criterion which applied to all storm events was that they must generate 0.03 meters of runoff in the Parhsall flumes in order to trigger data collection. Any rain event which did not generate at least 0.03 meters of runoff was not considered significant for this study.

Results and Discussion

TSS

Wilcoxon and ANOVA statistical analysis tests were used to compare TSS values before and after treatment by the BMPs. These tests displayed no significant effect the majority of the time for TSS reductions. Only five out of the twelve treatment combinations showed a significant difference between inflow and outflow TSS. This could be partially due to lateral inflow entering the channel between sensor stations and lack of maintenance of BMPs. These factors were not within the control of this study. Evidence of water scouring around BMPs was common at the research sites (see Figures D.1 through D.5 in Appendix D, pp. 79–84) display common BMP failures from poor installation, maintenance, and/or inspection negligence. Table D1 displays a summary of the parameters for the storms immediately prior the noted BMP issues.

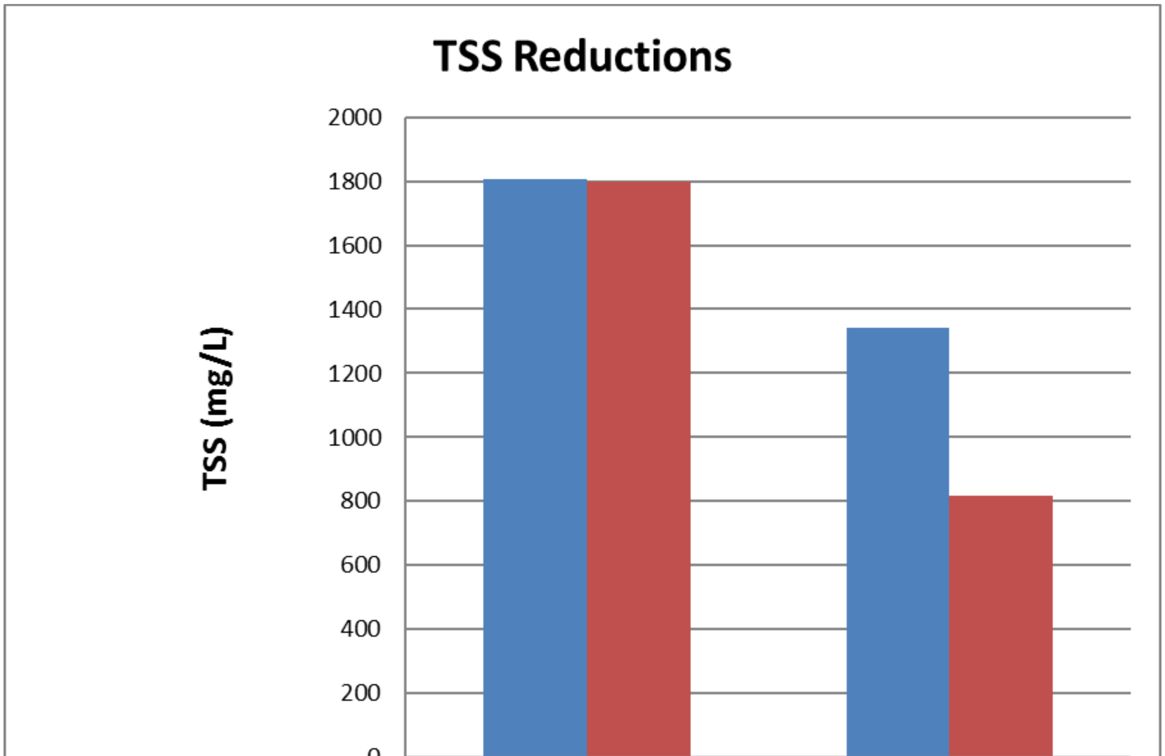
The mid-state site had on average higher TSS values entering the linear sediment control channels shown in Figure 4.9. The coastal and mid-state and upstate research sites discharged into sediment basins where further suspended solids were trapped. The application of PAM consistently showed reductions in TSS, without PAM the average time weighted TSS displayed mixed results.



	CNoPAM	CPAM	MNoPAM	MPAM	UNoPAM	UPAM
Time Weighted TSS AVG-IN	1296	726	2990	2433	1469	696
Time Weighted TSS AVG-OUT	1040	372	3589	1888	1271	326

Figure 4.9: Graph and corresponding index showing TSS values collected at TOC sampling stations.

After looking at the various BMPs and regions, when looking at the effect of adding flocculants (PAM) to the BMPs, PAM does have a statistically positive impact on reducing the total suspended solids (TSS) of the effluent. Figure 4.10 below shows the reductions of TSS when PAM is applied.



	NoPAM	PAM
Time Weighted TSS AVG-IN	1805	1341
Time Weighted TSS AVG-OUT	1797	818

Figure 4.10: Graph and corresponding index showing time weighted average TSS values across all sampling stations.

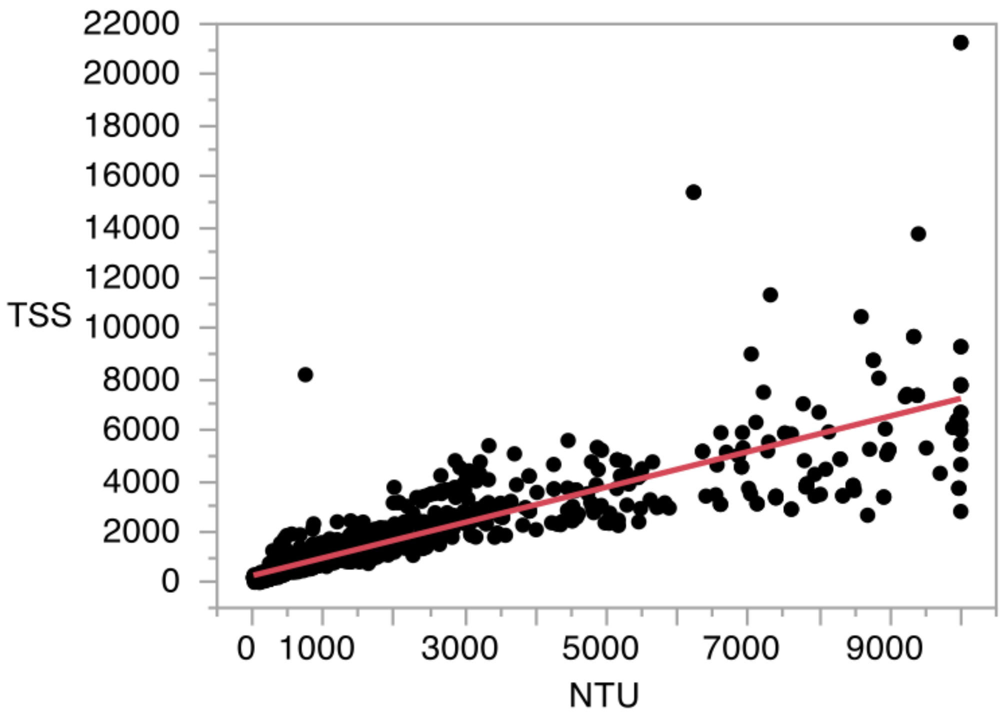
Turbidity and TSS Relationship

For comparative purposes, samples were analyzed for TSS and turbidity. Using the Pearson Product-Moment Correlation statistic test, TSS and Turbidity was tested to determine the correlation between the two independent variables (Figure 4.10). The Pearson product-moment correlation coefficient measures the strength of the linear relationship between two variables. If there is an exact linear relationship between two variables, the correlation is 1 or –1; depending on whether the variables are positively or negatively related. If there is no linear relationship, the correlation tends toward zero. The correlation value determined between turbidity and TSS from the water samples collected was 0.8550 indicating a strong association between the two variables. Additionally, a Summary of Fit report was running to provide a R^2 value. R Square (also called the coefficient of multiple determination) measures the degree of fit. The value can range from 0, indicating no fit, to 1 indicating an exact fit. The data set analyzed in this study (shown in Figure 4.11) found a R^2 value of 0.9316, suggesting a high correlation.

Table 4.2: ANOVA, and non-parametric statistical tests of the null-hypothesis (Ho= No difference between TOC and BOC, p value (Pr>F) > .05 then reject Ho and accept Ha).

TSS				
Identifier	**Statistical Test**	**p value**	**Statistical Test**	**Pr > F**
Upstate RDC	WILCOXAN	0.0408	Anova	0.0297
Upstate RDC	WILCOXAN	0.0001	Anova	0.0001
Upstate RDC-WS	WILCOXAN	0.001	Anova	0.003
Upstate RDC-WS	WILCOXAN	0.0002	Anova	0.001
Midstate W	WILCOXAN	0.1008	Anova	0.228
Midstate RDC - WS	WILCOXAN	0.0478	Anova	0.0247
Midstate RDC - WS	WILCOXAN	0.0007	Anova	0.0005
Coastal W	WILCOXAN	0.0004	Anova	0.0001
Coastal W	WILCOXAN	0.0019	Anova	0.0011
Coastal RDC-WS	WILCOXAN	0.0472	Anova	0.022
Coastal RDC-WS	WILCOXAN	0.0928	Anova	0.0004
Coastal RDC	WILCOXAN	0.0001	Anova	0.0001
Coastal RDC	WILCOXAN	0.105	Anova	0.0146

Regression Plot



Lack of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack of Fit	761	1006874421	1323094	1.4605
Pure Error	338	306198757	905913	**Prob > F**
Total Error	1099	1313073179		<.0001*
				Max RSq
				0.9316

Figure 4.11: Graph and index of values assigned after a best fit analysis was conducted. Max RSq value is the maximum R square that can be achieved by a model based only on these effects. Data paired, TSS and corresponding turbidity value from sample.

Table 4.3: Table of laboratory analysis observations; TSS mean percent changes.

Treatment	Time Weighted TSS AVG	Time Weighted TSS AVG	TSS
	IN	OUT	Diff
C-RDC	139.1666667	178.3333333	-28%
C-RDC	214.0350877	584.1666667	-173%
US-RCD	1318	172	87%
US-RCD	759.6666667	2491.43	-228%
US-RCD	1160	1573.571429	-36%
			-76%
C-RDC	251.6666667	202.5	20%
C-RDC	445.6140351	289.4736842	35%
US-RDC	478	75.5	84%
			46%
MID-RDC-WS	3134.883333	3558.65	-14%
MID-RDC-WS	3807.2	4940.15	-30%
MID-RDC-WS	1667.240741	1299.775	22%
US-RDC-WS	1614.285714	1240.714286	23%
US-RDC-WS	2491.43	879.047619	65%
C-RDC-WS	315	338.3333333	-7%
C-RDC-WS	387.78	558.35	-44%
			2%
MID-RDC-WS	1922.416667	1279.875	33%
MID-RDC-WS	1932.15		
US-RCD-WS	914.7619048	576.6666667	37%
C-RDC-WS	1438.333333	331.6666667	77%
			49%
C-SEDTUBES	2835.97	2725.833333	4%
C-SEDTUBES	3885.833333	1856.666667	52%
MID-W	3351.458333	4557.583333	-36%
			7%
C-SEDTUBES	1070	755	29%
C-SEDTUBES	426.3157895	283.3333333	34%
MID W	1416.6	874.64	38%
MID W	4460.438596	3509.208333	21%
			31%

Averages without PAM
Averages with PAM

Conclusions

Research on active construction sites analyzed the impact of rock ditch checks (RDCs), rock ditch checks with washed #57 stone on the upstream face (RDC-WS), and sediment tubes (W, Wattles) with and without PAM on TSS values. It was observed that RDCs with PAM, RDC-WS with PAM, and wattle structures with PAM decreased mean TSS values. On average, TSS decreased for all recorded storms using BMPs in conjunction with PAM. It was also observed that improperly maintained BMPs resulted in an increase of TSS. Based on this research, proper maintenance and regular inspections should be a priority in reducing TSS. Infrequent or improper BMP maintenance can result in higher TSS and lower trapping efficiencies as shown in Appendix D.

CHAPTER FIVE
SUMMARY CONCLUSION

Research on active construction sites analyzed how various BMPs both with and without PAM would reduce turbidity and TSS in effluent discharges. This analysis evaluated the impact on turbidity of sediment wattles, rock ditch checks (RDCs) and rock ditch checks with washed #57 stone on the upstream face (RDC-WS) at three active roadway construction sites in the upstate, mid-state, and coastal regions of South Carolina. It was observed that both RDC and RDC-WS with a PAM treatment were most effective in reducing turbidity with an average turbidity decrease of 58-63%. Wattles with a PAM treatment reduced turbidity values on average by 36%. Without PAM, a small increase in turbidity by an average of 5% occurred for RDC-WS while RDCs showed a 57% increase. These increases are thought to be partly caused by resuspension of sediment in the channel. Wattles without PAM decreased turbidity by an average of 26%.

It was observed that RDCs, RDC-WS, and wattle structures with PAM decreased mean TSS values. It was also observed that improperly maintained BMPs resulted in an increase TSS.

Based on this research, proper maintenance and regular inspections should be a priority in reducing TSS and turbidity (Appendix D). Infrequent or improper BMP maintenance can result in higher TSS and lower trapping efficiencies.

The observations made during this study with respect to the efficacy of BMPs and the use of PAM should lead to a recommendation of using PAM on linear construction sites. PAM consistently caused turbidity reductions and TSS reductions for all storms monitored. However, the extent of both percentage reduction and numeric reduction varied based on storm and runoff characteristics. All tests in this study involved 100 grams of granular PAM, sprinkled on the top and upstream face of each sediment tube, rock ditch check, and rock ditch check with size 57 washed stone relevant to the research. Based on this study, such a specification should ensure effective PAM is constantly present in order to reduce turbidity of runoff during a storm event.

APPENDICES

Appendix A

Turbidity data collected and environmental parameters recorded for Chapter 3:

Linear Sediment Control Best Management Practice Assessment Across

Three Distinct Eco-Regions of South Carolina

Appendix A contains data relevant to the effectiveness of PAM for turbidity reduction, the turbidity parameters for all runoff events of interest as well as relevant changes to the instruments and best management practices in the research channel. The raw data from the instruments would have taken up hundreds of pages, as readings were collected every minute at two instrument stations during runoff events. A description of the calculation of these parameters can be found in the Results and Discussion section of Chapter 3.

Table A1: Summary table of turbidity parameters gathered from field site monitoring equipment.

Date	Mean Inflow FNRU	Mean Outflow FNRU	% Difference	Location	Treatment	Treatment + Location
6/13/2015	9.202264178	3.894024477	57.68406121	Darlington	W-PAM	Darlington W-PAM
6/23/2015	804.6155667	115.2811237	85.67252132	Darlington	RDC-WS	Darlington RDC-WS
7/1/2015	4.499351191	6.152541	-36.74284889	Darlington	RDC-WS	Darlington RDC-WS
8/7/2015	543.2451357	101.4474584	81.32565729	Darlington	RDC-WS-PAM	Darlington RDC-WS-PAM
10/5/2015	53.27463593	94.09517861	-76.62284682	Darlington	RDC-WS	Darlington RDC-WS
11/19/2015	185.3863038	97.21592756	47.56035071	Darlington	RDC-WS	Darlington RDC-WS
4/20/2015	902.8542645	241.1945727	73.28532608	Darlington	W	Darlington W
5/11/2015	531.0724042	311.6912471	41.30908618	Darlington	W-PAM	Darlington W-PAM
6/3/2015	916.0901671	400.7881458	56.25014216	Darlington	W-PAM	Darlington W-PAM
11/22/2015	217.0220202	137.5514333	36.61867438	Darlington	RDC-WS	Darlington RDC-WS
12/23/2015	455.6141184	146.7603703	67.78844985	Darlington	RDC-WS	Darlington RDC-WS
11/26/2013	430.1590617	949.3862721	-120.7058636	Boiling Springs	RDC	Boiling Springs RDC
12/14/2013	559.2869965	775.5481713	-38.66729894	Boiling Springs	RDC-PAM	Boiling Springs RDC-PAM
2/21/2014	1167.385296	1327.489686	-13.71478559	Boiling Springs	RDC-WS	Boiling Springs RDC-WS
3/6/2014	437.1699584	638.2854842	-46.00396754	Boiling Springs	RDC-WS	Boiling Springs RDC-WS
7/2/2014	947.7408102	383.4668867	59.5388441	Boiling Springs	RDC-WS-PAM	Boiling Springs RDC-WS-PAM
1/22/2014	318.3953647	117.8797719	62.97691959	Boiling Springs	RDC-PAM	Boiling Springs RDC-PAM
2/4/2014	314.2618983	192.5739826	38.72181653	Boiling Springs	RDC	Boiling Springs RDC
4/19/2014	993.7470275	265.5321846	73.27970024	Boiling Springs	RDC-WS-PAM	Boiling Springs RDC-WS-PAM
6/30/2017	48.90961851	30.42250651	37.79852014	Summerville	W	Summerville W
7/10/2017	128.1415361	49.14008073	61.65171557	Summerville	W	Summerville W
8/4/2017	189.0584767	162.8965585	13.83800327	Summerville	W-PAM	Summerville W-PAM
9/11/2017	286.7777354	284.0665739	0.945387728	Summerville	RDC-WS	Summerville RDC-WS
2/9/2018	248.528276	97.67346809	60.69925336	Summerville	RDC	Summerville RDC
3/10/2018	260.9292045	61.02378757	76.61289479	Summerville	RDC-PAM	Summerville RDC-PAM
3/12/2018	176.1572308	50.60717192	71.27158978	Summerville	RDC-PAM	Summerville RDC-PAM

Date	Mean Inflow FNRU	Mean Outflow FNRU	% Difference	Location	Treatment	Treatment + Location
8/13/2017	134.9817732	165.2875384	-22.45174623	Summerville	W-PAM	Summerville W-PAM
8/22/2017	920.8808804	56.9587725	93.81475132	Summerville	W-PAM	Summerville W-PAM
9/6/2017	534.3499192	136.3026941	74.49186587	Summerville	RDC-WS	Summerville RDC-WS
12/8/2017	352.0904014	240.7306254	31.6281772	Summerville	RDC-WS-PAM	Summerville RDC-WS-PAM
1/29/2018	48.80444021	93.89056537	-92.38119516	Summerville	RDC	Summerville RDC
11/23/2017	222.9230981	92.83313058	58.35643261	Summerville	RDC-WS-PAM	Summerville RDC-WS-PAM

Table A2: Raw data used in lab analysis of runoff collected from research sites, data was paired by sample bottle. Blank values or zeroes indicate missing values.

Treatment	Coastal	Mid-state	Upstate	IN	Sum	Mean	Sum	Mean	Sum
C-RDC-IN	48	0	0	48	3892	82.80851	13354	278.2	-8064.63
C-RDC-IN-PAM	46	0	0	46	13232.6	287.6652	4626	100.6	193.9773
C-RDC-WS-IN	43	0	0	43	9889	229.9767	9896	230.1	32.66931
C-RDC-WS-IN-PAM	37	0	0	37	26558	717.7838	8651	233.8	-284.962
C-SEDTUBES-IN	48	0	0	48	202395	4216.563	2.00E+05	3127	262.4021
C-SEDTUBES-IN-PAM	48	0	0	48	53061.9	1128.977	22857	476.2	-135.216
MID-RDC-WS-IN	0	46	0	46	165030	4025.122	3.00E+05	5859	-4118.77
MID-RDC-WS-IN-PAM	0	48	0	48	60604	2525.167	37372	778.6	786.4362
MID-W-IN-	0	24	0	24	—	—	0	0	—
MID-W-PAM	0	42	0	42	146360	3569.756	2.00E+05	4198	895.028
UP-RDC-WS	0	0	41	41	93711	2285.634	56337	1374	1315.974
UP-RDC-WS-PAM	0	0	48	48	39486	822.625	59616	1242	2589.354
US-RDC-IN	0	0	72	72	115396	1602.722	1.00E+05	1533	902.5175
US-RDC-IN-PAM-1	0	0	48	48	39486	822.625	19863	413.8	2589.354

Appendix B

TSS data collected and recorded for Chapter 4: Assessing Linear Sediment Control Best Management Practices Effects on Total Suspended Solids Across Three Distinct Eco-Regions of South Carolina

Appendix B contains data relevant to the effectiveness of BMPs for TSS reduction, the TSS parameters for all runoff events of interest as well as relevant changes to the instruments and best management practices in the research channel. A description of the calculation of these parameters can be found in the Results and Discussion section of Chapter 4.

Table B.1: Raw data of TSS values determined from lab analysis.

TREATMENT	Sum	Mean
C-RDC-IN	8050	171.2766
C-RDC-IN-PAM	16600	353.1915
C-RDC-OUT	20450	426.0417
C-RDC-OUT-PAM	11450	243.617
C-RDC-WS-IN	15350	356.9767
C-RDC-WS-IN-PAM	33800	913.5135
C-RDC-WS-OUT	19050	453.5714
C-RDC-WS-OUT-PAM	18050	376.0417
C-SEDTUBES-IN	179550	3740.625
C-SEDTUBES-IN-PAM	51200	1089.362
C-SEDTUBES-OUT	120550	2511.458
C-SEDTUBES-OUT-PAM	32100	668.75
MID W IN PAM	148110	3444.419
MID W OUT PAM	105498	2511.845
MID-RDC-WS-IN	216882	3098.314
MID-RDC-WS-IN-PAM	97350	2028.125
MID-RDC-WS-OUT	268798	3733.299
MID-RDC-WS-OUT-PAM	37713	1571.354
MID-W-IN	95833	3993.021
MID-W-OUT	123395	5141.458
US-RDC-IN	93260	1295.278
US-RDC-OUT	101790	2077.347
US-RDC-WS-IN-PAM	22360	931.6667
US-RDC-WS-OUT-PAM	12830	534.5833
US-RDC-IN-PAM	15646	651.9167
US-RDC-OUT-PAM	1750	72.91667
US-RDC-WS IN	100100	2441.463
US-RDC-WS OUT	57700	1202.083

Table B.2: Sample of storms with noted BMP failure and their corresponding TSS analysis.

Date	Rain (in.)	Treatment	Mean Before (TSS)	Mean After (TSS)	Mean Difference	Stat test	p value	Percent change
4/24/2015	0.95	Wattle	222.0833	960.4688	-738.3854167	Kruskal-Wallis rank sum test	1.2E-13	-332.481
7/2/2015	1.47	RDC-WS	235.3333	436.875	-201.5416667	Kruskal-Wallis rank sum test	2.2E-16	-85.6409
8/9/2017	1.53	Wattle	539.13	308.335	230.795	Kruskal-Wallis rank sum test	0.0659	42.80878
11/11/2017	4.53	RDC-WS	397.37	597.2	-199.83	Kruskal-Wallis rank sum test	0.0096	-50.2881
1/29/2018	0.54	RDC-WS	143.105	187.5	-44.395	Kruskal-Wallis rank sum test	0.2	-31.0227

Appendix C

Programming for Campbell Scientific instrumentation used in Chapters 3 and 4:

Linear Sediment Control Best Management Practice Assessment Across Three Distinct Eco-Regions of South Carolina

&

Assessing Linear Sediment Control Best Management Practices Effects on Total Suspended Solids Across Three Distinct Eco-Regions of South Carolina

Appendix C contains the text from the program run by the CR206x dataloggers during the study. It was written using the "CRBasic Editor" function of Campbell Scientific Loggernet software, with the assistance of Campbell Scientific engineers. When level of water in the flume exceeded 0.1 feet, as indicated by the CS451 pressure transducer, the program began collection of turbidity data using the OBS500 turbidimeter. The logger also sent a signal opening a steady state relay which caused the ISCO sampler to begin a time-based sampling protocol. This sampler trigger worked by keeping the trigger pin of the sampler grounded (relay closed) until it was time for sampling, at which point the ground was removed (relay open).

Initially the program was created to include regular movement of the shutter to wipe the lenses clean. However, this mechanism consistently became jammed by sediment particles which made data collection impossible. In the normally dry environment of a runoff conveyance channel, the wiping mechanism was not necessary so that part of the program was "commented out," meaning an apostrophe was put in front of the text to make it a comment and not an active part of the program. This text was left in the program and this appendix because in other applications the wiping mechanism might be useful, for example in a pond where algae growth could be an issue. Additional time was added to the 5-volt current sent to the ISCO sampler in order to enable sampling to begin.

```
'CR200/CR200X Series
'Program Karl Lambert
'Modified by Ron Goodrich 6/14/2016, again on 7/20/2016
'Modified by Boyd Bringhurst 7/26/2013.  Open and close counts are meaningless since
if it
' reports how far the shutter moves, not its' position.  I commented that logic out and
' put in an open shutter before the program starts to run so that it will start in a known
state.

'This version of the program is set to apply 5 volts to pin F
'of the sampler to enable the sampler program.
'Using CSI cable 10164-L The green wire is connected to
'to pin F on the ISCO6712. Connect the green wire to VX1.  The control
'will enable the sampler when the level rises above 0.1ft and the
'manual control for the sampler (Sampler_Enabled) is >= 1.

'Declare Variables and Units
Public BattV
Public OBS500(9)
Public CS450(2)
Public Enc_RH
Public Sampler_Enabled
Public TimeCounter
Public obsDatOpen(4),obsDatClose(4)
Public Trigger,Open,Close
Public Five_Min_Int
Dim i

Units BattV=Volts
Units Enc_RH=%,

Alias CS450(1) = Lvl_ft
Alias CS450(2) = TempC_CS450
```

```
Units Lvl_ft = ft
Units TempC_CS450 = deg C


Alias OBS500(1) = turb_bs
Alias OBS500(2) = turb_ss
Alias OBS500(3) = Turb_Ratio
Alias OBS500(4) = tempC_obs500
Alias OBS500(5) = raw_obs
Alias OBS500(6) = raw_ss
Alias OBS500(7) = open_current
Alias OBS500(8) = close_current
Alias OBS500(9) = wet_dry

Units turb_bs = fbu
Units turb_ss = fnu
Units ratio = fnru
Units tempC_obs500 = degC
Units raw_obs = volts
Units raw_ss = volts
Units open_current = mA
Units close_current = mA
Units wet_dry = YesNo

'Define Data Tables
DataTable(DataTable,Lvl_ft > Trigger,-1)
  DataInterval(0,1,Min)
  Minimum(1,BattV,False,False)
  Sample (2,CS450())
  Sample (9,OBS500())
  Sample (1,Sampler_Enabled)
  Sample (1,Enc_RH)
EndTable

DataTable (Five_Min_Int,True,-1)
  DataInterval(0,5,Min)
  Sample (1,Five_Min_Int)
  Average (1,Lvl_ft,False)
  Minimum (1,Lvl_ft,False,false)
  Maximum (1,Lvl_ft,False,false)
  Average (1,BattV,False)
  Average (1,TempC_CS450,False)
  Average (1,turb_bs,False)
```

```
  Average (1,turb_ss,False)
  Average (1,Turb_Ratio,False)
  Average (1,tempC_obs500,False)
  Sample (5,OBS500(5))

EndTable


'Main Program
BeginProg

  Trigger = 0.6
  'ExciteV (Ex1,mV5000)
  SWBatt (1 )
  SDI12Recorder (obsDatOpen(),"0M3!",1.0,0)
  Close = 0
  Open = 1
  obsDatOpen(1) = 20800
  For i = 1 To 9
    OBS500(i) = -99
  Next i

  Scan(1,min)
    'Default Datalogger Battery Voltage measurement 'BattV'
    Battery(BattV)

    'CS450/CS455 Pressure Transducer measurements
    'Lvl_ft' and 'Temp_C_2'
    SDI12Recorder(Lvl_ft,"1M2!",1,0)
    Lvl_ft=Lvl_ft*2.30666
    If Lvl_ft > Trigger Then TimeCounter = TimeCounter + 1
    If Lvl_ft < (0.9*Trigger) Then TimeCounter = 0

    'OBS500 Wiper Control
    'If Lvl_ft > Trigger Then
    ' If TimeCounter MOD 60 = 0 Then
    '  SDI12Recorder (obsDatClose(),"0M7!",1.0,0)
    ' SDI12Recorder (obsDatOpen(),"0M3!",1.0,0)
    'EndIf
    'EndIf

    'OBS500 Smart Turbidity Meter (SDI-12)
    'will only sample if the water level is above 0.1 ft.
    'Close OBS500 if water level is below needed measurement height
```

```
'If Lvl_ft < (0.9*Trigger) AND Close < 0.5Then
'SDI12Recorder (obsDatClose(),"0M7!",1.0,0)
'If obsDatClose(1) > 20000 Then
'Close = 1
' Open = 0
'  EndIf
' For i = 1 To 9
'  OBS500(i) = -99
'Next i
'EndIf

If Lvl_ft > Trigger AND Open < 0.5 Then
  SDI12Recorder (obsDatOpen(),"0M3!",1.0,0)
  If obsDatOpen(1) > 20000 Then
    Close = 0
    Open = 1
  EndIf
EndIf

If TimeCounter >= 1 Then
  SDI12Recorder(OBS500(),"0M6!",1,0)
EndIf

'CS210 measurement 'Enc_RH'
PortSet(2,0)
VoltSe(Enc_RH,1,1,0.1,0)

'Sampler Control Section
'if the water level rises to 0.1 ft the sampler will be enabled and
'and stay enabled.
If Lvl_ft > Trigger Then  'units of ft
  ExciteV (Ex1,mV5000)
  Delay (15,Sec)
  ExciteV (Ex1,mV0)
EndIf

'Call Data Tables and Store Data
CallTable(DataTable)
CallTable (Five_Min_Int)

NextScan
```

Appendix D

Additional figures from Chapter 4: Assessing Linear Sediment Control Best Management Practices Effects on Total Suspended Solids Across Three Distinct Eco-Regions of South Carolina

Figure D.1: Mid-state research site, scour around wattles — 05/18/15.


Figure D.2: Coastal research site, wattle failure and lack of channel maintenance — 08/15/2017.

Figure D.3: Coastal research site, side scour around RDC-WS — 11/16/2017.

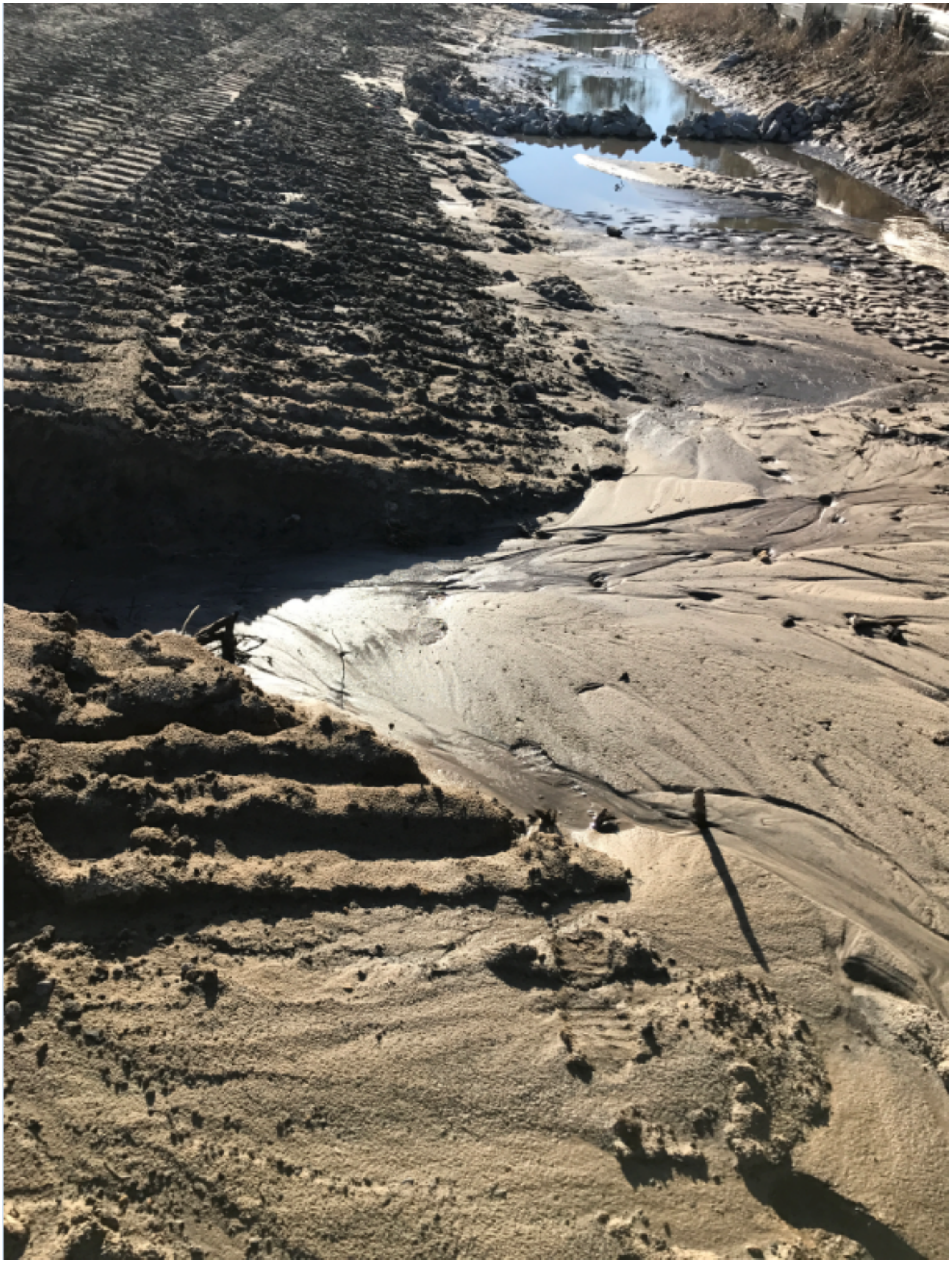


Figure D.5: Coastal research site runoff channel formed perpendicular to sediment control channel, and RDC failure — 01/31/2018.

Figure D.5: Mid-state research site, improper RDC-WS installation — 07/11/2015.

LITERATURE CITED

Alabama Department of Transportation (ALDOT). 2012. Alabama Standard Specifications, Special Provisions, Section 672 Stormwater Turbidity Control. Available at: http://www.dot.state.al.us/conweb/doc/Specifications/2012_GASP.pdf. Accessed 3/17/2014.

Auckland Regional Council. 2004. The use of flocculants and coagulants to aid the settlement of suspended sediment in earthworks runoff: Trials, methodology and design [draft], June 2004. Auckland Regional Council Technical Publication 227. Auckland, New Zealand: Beca Carter Holling & Ferner Ltd.

Babcock, D.L. and R.A. McLaughlin. 2013. Erosion control effectiveness of straw, hydromulch, and polyacrylamide in a rainfall simulator. *Journal of Soil and Water Conservation* 68(3): 221-227.

Berry, J. W. 2012. Master's thesis. Clemson University. *Sediment Based Turbidity and Bacteria Reduction Analysis in Simulated Construction Site Runoff*.

Burkey, J. O. 2014. Master's thesis. Clemson University. *Evaluation of Turbidity Reduction with Linear Sediment Control Best Management Practices*.

Bhardwaj, A. K. and R. A. McLaughlin. 2008. Simple polyacrylamide dosing systems for turbidity reduction in stilling basins. *Transactions of the ASABE* 51(5): 1653-1662.

Campbell Scientific. 2013. OBS500 Smart Turbidity Meter: Operator's Manual. Available at: http://s.campbellsci.com/documents/us/manuals/obs500.pdf. Accessed 4/04/2014.

Borrelli, P., P. Panagos, M. Märker, S. Modugno and B. Schütt. 2017. Assessment of the impacts of clear-cutting on soil loss by water erosion in Italian forests: CATENA, Volume 149, Part 3, 2017. 770-781.

Clark, E. H. 1985. The off-site costs of soil erosion. *Journal of Soil and Water Conservation* 40(1): 19-22.

Entry, J. A., D. Mills, K. Jayachandran and R. E. Sojka. 2013. High polyacrylamide application rates do not affect eubacterial structural diversity. *Water, Air, & Soil Pollution* 224. 162.

Florida Department of Transportation (FDOT). 2013. Erosion and Sediment Control Designer and Reviewer Manual Available at: http://www.dot.state.fl.us/rddesign/Hydraulics/files/Erosion-Sediment-Control.pdf.

Hach Company. 2012. 2100AN Laboratory Turbidimeter, Specifications. Available at: http://www.hach.com/2100an-laboratory-turbidimeter-epa-115-vac/product-details?id=7640450972.

Kang, Jihoon, Amoozegar, Aziz, Heitman, Joshua L. and McLaughlin, Richard A. 2014. Granular and Dissolved Polyacrylamide Effects on Erosion and Runoff under Simulated Rainfall. *Journal of Environmental Quality*; Madison.

Kang, J., M. M. McCaleb and R. A. McLaughlin. 2014. Check dam and polyacrylamide performance under simulated stormwater runoff. *Journal of Environmental Management* 129(0): 593-598.

LaGrega, M. D., P. Buckingham and J.C. Evans. 2001. Waveland Press, Inc., Long Grove, IL. *Hazardous Waste Management*. Ch. 4, Fate and Transport of Contaminants.

Lentz, R. D., R. E. Sojka and B. E. Makey. 2002. Fate and Efficacy of Polyacrylamide Applied in Furrow Irrigation: Full-Advance and Continuous Treatments. *Journal of Environmental Quality* 31661-670. 163.

McLaughlin, R. A., S. E. King and G. D. Jennings. 2009. Improving construction site runoff quality with fiber check dams and polyacrylamide. *Journal of Soil and Water Conservation* 64(2): 144-154.

McLaughlin, R. A. 2006. Polyacrylamide Blocks for Turbidity Control on Construction Sites. 2006 ASAE Annual Meeting (Paper # 062254).

McLaughlin, R. A. and T. T. Brown. 2006. Evaluation of erosion control products with and without added polyacrylamide. *JAWRA Journal of the American Water Resources Association* 42(3): 675-684.

North Carolina Department of Transportation (NCDOT). 2008. Erosion and Sediment Control Details. NCDOT Roadside Environmental Unit. Available at: http://www.ncdot.gov/doh/operations/dp_chief_eng/roadside/soil_water/details/.

North Carolina Department of Transportation (NCDOT). 2013. Erosion and Sediment Control Planning and Design Manual Available at: http://portal.ncdenr.org/web/lr/publications.

Pimentel, D., C. Harvey, P. Resosudarmo, K. Sinclair, D. Kurz, M. McNair, S. Crist, L. Shpritz, L. Fitton, R. Saffouri, and R. Blair. 1995. Environmental and Economic Costs of Soil Erosion and Conservation Benefits. *Science* 24 Feb 1995: 1117-1123.

R. Perkins, B. N. Wilson, J. S. Gulliver and B. Hanson. 2017. Relationship between suspended sediment concentration and turbidity at construction sites. *Journal of Soil and Water Conservation* January/February 2017 vol. 72 no. 1, 26-35.

Rabiou, N. 2005. Master's thesis. University of Missouri at Columbia. *Polyacrylamide Application for Upland Erosion Control*.

Sojka, R. E., D. L. Bjorneberg, J. A. Entry, R. D. Lentz and W. J. Orts. 2007. Polyacrylamide in Agriculture and Environmental Land Management. Volume 92(1): 75-162.

Soupir, M. L., S. Mostaghimi, A. Masters, K. A. Flahive, D. H. Vaughan, A. Mendez and P. W. McClellan. 2004. Effectiveness of polyacrylamide in improving runoff water quality from construction sites. *JAWRA Journal of the American Water Resources Association* 40(1): 53-66.

South Carolina Department of Natural Resources (SCDNR). 2014. South Carolina State Climatology Office. Number of Rain Days. Available at: http://www.dnr.sc.gov/climate/sco/ClimateData/cli_sc_climate.php#precipitation.

South Carolina Department of Health and Environmental Control (SCDHEC). 2005. *Best Management Practice Handbook*. Available at: https://www.scdhec.gov/environment/water/swater/docs/BMP-handbook.pdf.

Shoemaker, A. L., W. C. Zech and T. P. Clement. 2012. *Laboratory-Scale Evaluation of Anionic Polyacrylamide as an Erosion and Sediment Control Measure on Steep-Sloped Construction Site*s. American Society of Agricultural and Biological Engineers, St. Joseph, Michigan www.asabe.org

Tempel, E. A. 2011. Master's thesis. Clemson University. *Fate and Transport of* Escherichia coli *Within Sediment Basins on Active Construction Sites*.

Teledyne ISCO. 2011. *ISCO Open Channel Flow Measurement Handbook*. Sixth Edition. Chapter 13: Parshall flume Discharge Tables.

Toronto and Region Conservation. 2010. Performance Evaluation of an Anionic Polymer for Treatment of Construction Runoff. Available at: http://sustainabletechnologies.ca/wp/wp-content/uploads/2013/01/PolymerEvaluationReport-Final-compressed.pdf.

U.S. Environmental Protection Agency (EPA). 1993. Method 180.1 Determination of Turbidity by Nephelometry. Environmental Monitoring Systems Laboratory Office of Research and Development. Cincinnati, OH.

U.S. Environmental Protection Agency (EPA). 2014. Revisions to the Construction and Development Effluent Guidelines; Final Rule. Office of Water (4303T). EPA 820-F-14-001. 165.

U.S. Environmental Protection Agency (EPA). 2005. Stormwater Phase II Final Rule: Construction Site Runoff Control Minimum Control Measure. Office of Water (4203). EPA 833-F-00-008, Fact Sheet 2.6.

U.S. Environmental Protection Agency (EPA). 2012. Water: Monitoring & Assessment. 5.5 Turbidity. Available at: http://water.epa.gov/type/rsl/monitoring/vms55.cfm. Accessed 4/24/2012.

U.S. General Accounting Office (USGAO). 1998. Oregon watersheds: many activities contribute to increased turbidity during large storms. GAO/RCED-98-220. Washington, D.C.

U.S. Geological Survey (USGS). 2004. New Turbidity Data Reporting Procedures. Available at: http://water.usgs.gov/owq/turbidity/TurbidityInfoSheet.pdf. Accessed 4/04/2014.

Wilson, A. D. and Crisp, S. (1975). Rigid highly carboxylated ionic polymers. In "Ionic Polymers" (L. Holiday, Ed.), pp. 208-260. Chapman and Hall, New York.

Zech, W. 2014. Assessing the Performance of a Sediment Basin at a Construction Site in Franklin County, Alabama. In *Proceedings of IECA Environmental Connection 2014* (25-28 February 2014, Nashville, TN) IECA February 2014.